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FEBRUARY 1960

STRUCTURAL SIGNIFICANCE OF TERTIARY VOLCANIC ROCKS IN SOUTHWESTERN UTAH

J. HOOVER MACKIN

Department of Geology, University of Washington, Seattle

ABSTRACT. Most of the silicic volcanic rocks of the Great Basin are ignimbrites rather than lava flows. The more common types were probably formed by nuées ardentes which spread laterally as density currents of very high fluidity, but there are aberrant types that may be in some manner transitional between ignimbrites and lava flows, and the whole problem of mechanism of origin is as yet little understood. Uncertainty on this score is of no concern here; mapping of many of the units indicates that, whatever their origin, they assumed a distribution approaching that of an equal volume of water, filling valleys to a common level and forming sheets of substantially uniform thickness where the relief of the pre-existing surface was low. Some of the individual ignimbrites are many hundreds of feet thick and have an areal extent of as much as 10,000 square miles. Because each of these extensive and initially flat sheets were formed everywhere at the same instant of time, they are very nearly ideal stratigraphic units. They occur in most parts of the Great Basin and range in age through most of the Tertiary.

Eleven ignimbrites which are widespread in southeastern Utah are described and given formal stratigraphic names. The fact that the oldest of them lies unconformably across the beveled edges of thrusts and folds involving late Cretaceous strata indicates that the beginning of volcanic activity post-dates the Laramide orogeny. As planar units which provide a record of Tertiary crustal movements, the ignimbrites confirm the Gilbert theory, based originally on physiographic evidence, that block faulting has been the characteristic type of post-Laramide deformation in the Great Basin. The stratigraphic-structural approach makes it possible (1) to work out the geometry of the block faulting with a precision not obtainable by use of displaced erosion surfaces; (2) to deal with episodes of block faulting that occurred during the early Tertiary and are not expressed by the present topography; and (3) to crossdate these and other geologic events on a regional scale.

On the basis of detailed work in southwestern Utah, and reconnaissance elsewhere, it is stated as a deliberately provocative working hypothesis that block faulting has been the only type of regional tectonism in the Great Basin in post-orogenic time. The first requirement in testing this hypothesis is the recognition, as such, of flexures and thrust faults developed (1) by emplacement of hypabyssal intrusions, and (2) by gravity sliding from primary relief features raised by intrusion and block faulting. These two classes of structures are of much interest in their own right; their significance for present purposes is merely that they may be readily mistaken as evidences of regional tectonism. Equally critical is the need for distinguishing post-orogenic deformational effects from those produced during the orogeny. Examples are given of use of the ignimbrites in making these distinctions.

INTRODUCTION

It is now generally recognized that the silicic volcanic rocks of the Great Basin, commonly considered to be lava flows in early geologic reports, are nearly all ignimbrites; that is, as this term is used here, depositional units formed by eruptions of the nuée ardente type. Attention has been called by C. S. Ross (1955) to the widespread occurrence of these special kinds of pyroclastic rocks in the Cordilleran region, and individual units or sequences of units have been described in many places in the Great Basin and neighboring provinces in recent years (e.g. Mansfield and Ross, 1935; Gilbert, 1938; Callaghan, 1939; Enlows, 1955; Sabins, 1957).

My acquaintance with Great Basin volcanic rocks dates from the field seasons of 1950-52, which were spent largely in mapping a thick and varied sequence of them in the Iron Springs district in southwestern Utah for the U. S. Geological Survey (Mackin and Nelson, 1959). Mapping of adjoining areas (fig. 1) by University of Washington graduate students, R. L. Threet (1952) in the Red Hills to the northeast, E. F. Cook (1952, 1957) in the Pine Valley Mountains and W. R. McCarthy (in progress) in the Gunlock area to the south, H. R. Black (in progress) in the Bull Valley district to the southwest, G. M. Miller (1958) in the Wah Wah Range to the northwest, and E. H. East (1956) in the San Francisco Range to the north, has greatly broadened our knowledge of the stratigraphic succession worked out in Iron Springs, and has added many new units. An investigation of the basin-range problem in eastern Nevada in 1955, for the Gulf Oil Company, quickly resolved itself into a regional reconnaissance of the volcanic rocks because it was apparent that there, as in Iron Springs, the stratigraphy of these rocks is an indispensable key to an understanding of basin-range structure and topography. An unexpected dividend was the discovery that some of the Nevada units are definitely correlatable with units in southwestern Utah. E. F. Cook worked with me in Nevada early in the 1955 season, and has subsequently continued the stratigraphic study of the Nevada volcanics independently, paralleling similar work by me in the Great Basin in west central Utah during the 1955 and 1956 seasons. Threet (1952, 1956) has spent parts of several seasons extending his mapping eastward from the Red Hills into the Colorado Plateau. A tour to examine relationships between uranium ore deposits and igneous rocks in the Great Basin during 1957, in company with Atomic Energy Commission personnel familiar with geology in the vicinity of the ore bodies, provided an opportunity to observe, in many new places, volcanic sequences which for the most part conform with, or are instructive variations of, stratigraphic and structural patterns that have been determined in southwestern Utah over the past eight years.

The theme of this paper is a combination of two points suggested above: (1) that as depositional units that were deposited as essentially horizontal sheets, the Great Basin ignimbrites serve as ideal reference planes for measurement of Tertiary deformation, and (2), that as layers of great areal extent they provide a means of cross-dating Tertiary episodes of deformation, intrusion, metallization, and other geologic events, from place to place throughout much of the province. The concepts developed are based primarily on studies in southwestern Utah, but they are advanced here as working hypotheses applicable to the Great Basin as a whole. The hypotheses are outlined briefly, without the detailed statement of evidence and reasoning, the formal maps and sections, and the careful qualifications, that would be needed in presentation of a specific conclusion regarding a particular place. The treatment of a given hypothesis is intended, not to prove that it holds true in the area used as an example, but merely to establish its claim to consideration as a possible explanation of relationships of the type stated, in any area. When a point is set forth as a definite conclusion, this is a promise that it will be adequately documented in later reports. References to the literature are intended, not so much

to support the point under discussion, as to indicate that the same point has been made earlier by others.

The regional stratigraphic study of the Tertiary volcanics indicates that some individual ignimbrites are hundreds of feet in thickness over an area measured in many thousands of square miles. These great sheets represent the frothing eruption of many hundreds of cubic miles of magma, perhaps within a period measured in weeks or months. The total volume of Tertiary silicic volcanic rocks in the Great Basin is of the order of magnitude of 50,000 cubic miles. It seems reasonable to suppose that the transfer of so enormous a quantity of material from depth to the surface, in eruptive episodes that occurred from place to place and from time to time during the Tertiary, must be in some manner genetically related to episodes of block faulting that were in general similarly distributed in space and time (Longwell, 1950, p. 427-428). An early draft of this article called attention to the striking similarity in pattern relationships between basin-range structure and the sets of antithetically tilted slump blocks formed in clay which fails by reason of withdrawal of lateral support, and suggested that Great Basin block faulting is an expression of a comparable slump-creep movement of segments of the crust toward a "free side" created by the rapid expulsion of very large volumes of magma formed by fusion of crustal rock. But this "eruptive-tectonic" hypothesis for origin of basin-range structure ramifies persuasively in many directions—starting as an innocuous after-thought, it quickly became a Part II, equal in size to the original article. This overgrowth of an appendage wholly different in substance and approach from the body of the paper called for surgery—the present article, which treats the structural significance of the volcanic rocks in a descriptive sense, will be followed in a forthcoming issue of this journal by a sequel dealing with some possible genetic relationships between eruptive activity and deformation during the post-orogenic period in the Great Basin and neighboring provinces. The fact that there will be a sequel needs to be noted here because reference is made to it at a number of places in this article, and because discussion of some aspects of the timing and geometry of basin-range movements is deferred to it.

Both articles are bundles of working hypotheses, the first at the field relations level and the second at the level of underlying causes. Some of the interpretations that seem to fit the "facts" in southwestern Utah may be incorrect, and it is quite likely that concepts which are valid in that area may not hold true for the remainder of the Great Basin. But these are not serious defects in articles such as these; it is more important that a working hypothesis be provocative than that it be right. The merit of the articles depends on the extent to which, by giving new meanings to familiar relationships, and sharpening the perception for inter-connections that might otherwise be missed, they tend to accelerate the gathering and analysis of the data needed for an eventual understanding of the post-orogenic history of the Great Basin.

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IGNIMBRITES AS STRATIGRAPHIC UNITS

Terminology.—Discussion of volcanic rocks as stratigraphic units requires sets of terms which apply to and distinguish between (a) the depositional unit formed by a single eruptive episode, this being the basic stratigraphic element observed in the field, (b) the rock type or types comprising this unit, and (c) the eruptive mechanism. Terms are available to fit these needs, but because some of them have been applied in different and overlapping senses, it is necessary to state the manner in which they are used here. A review and discussion of the terminology of volcanic rocks is now in preparation by E. F. Cook.

The term "nuée ardente" was proposed by Lacroix (1908), and later modified by Perret (1935), for a special type of eruptive mechanism observed at Mount Pelée and La Soufrière. It is the general consensus that the nuée ardente originates by frothing of the magma and bursting of the bubbles of the froth to give rise to a mass of hot gas so charged with comminuted pumice as to be heavier than air; this mass "boils" from the vent, and moves downslope under the influence of gravity (see for example, Anderson and Flett, 1903, p. 394; Bell, 1942, p. 525-528; Fenner, 1923, p. 72; Finch, 1935; Williams, 1957, p. 59-65). In this respect the nuée ardente contrasts sharply with the genetically related Plinian eruptive mechanism, in which the fragmented pumice is violently propelled upward from the vent and spread laterally by winds, losing all or most of its heat before settling to the ground. The nuée ardente spreads laterally, on the ground, as a density current of very high mobility—it may attain hurricane velocity in a short distance and its charge of solid particles may be glowing hot when it comes to rest. Cauliflower clouds of ash and gas which rise from the surface of the density current phase are an integral part of the nuée; the contrasted deposits of the two phases are usually gradational.

"Nuée ardente" is widely used by students of modern volcanism for this general type of eruption, readily qualified as Pelécan, Katmaian, and so on, to designate nuées with the particular habits of those observed at those places. If we may judge by the thickness, lateral extent, degree of welding, and other features of their deposits, the Tertiary eruptions of the Great Basin would compare with those of modern times as the explosion of a hydrogen bomb with the bursting of a firecracker. Because they are of an altogether different order of magnitude, there is no reason to believe that the observed eruptions are

good models of those of the past. It is probably true, as pointed out by Howel Williams (oral communication) that most of the Tertiary nuées issued from fissures rather than from central vents, but to call them "nuées ardentes of the fissure eruption type" would be to beg a very important question. "Nuée ardente of the Great Basin type" has some advantages, but anyone familiar with the rocks in question is aware that they represent a wide variety of mechanisms of eruption and spreading, which are not well understood. In this paper "nuée ardente" without qualifiers merely means that the characteristics of the ancient pyroclastic deposits indicate an eruptive mechanism, the closest approach to which in modern times is that to which this term was applied by Lacroix and Perret. The alternative is to invent a new word, and the only justification for so doing is the argument that "nuée ardente" should be restricted to the small scale eruptions to which it was first applied. This pious thought is not realistic. As indicated above, the term has been used loosely, generally for the type of eruption which operates as a density current, by many workers for many years; its virginity could not be restored, even if it were desirable to do so.

An understanding of the mechanism of origin of the volcanic rocks of the Great Basin depends primarily on accumulation of data regarding such factual matters as the areal extent of individual units constituting the Tertiary succession; the principal types of units represented; and lateral and vertical variations in degree of welding, size of rock fragments and crystals, and the many other lithologic features that characterize each type—until these things are known we do not even know what a theory of origin must account for. The first essential step in this direction is the working out of the regional stratigraphy of the volcanic rocks; we are now in this stage of the investigation. Origin is not an issue in this article—the concept stated above in oversimplified form, that the ignimbrites were spread laterally as density currents of very high fluidity, is significant only in that it provides a rational explanation for their observed habits of form and distribution. These rhyolitic and latitic units nowhere exhibit the bulbous forms that are characteristic of silicic lava flows, but show instead a distribution approaching that which would be assumed by sheets of water, surrounding hills and filling lowlands and valleys to a common level.

Zirkel used "welded" and "fused" at a number of places in his descriptions of silicic rocks of the Fortieth Parallel collections, for example, "a pumice-breccia which the microscope discovers to be composed of numerous fragments welded or cemented closely together" (1876, p. 267). It is clear that he was aware of the unusual nature of these rocks, but his meaning of "welded" seems to have been quite different from its present meaning as applied to volcanics. The term was first used in the modern sense by Iddings in discussion of the microscopic features of a volcanic rock occurring in Yellowstone Park; he described the structure as "a confusedly twisted arrangement of glass fibres and films," and suggested that the rock might have been formed "by exploded fragments of molten material . . . which fall together in a heated condition, plastic enough to weld together in a compact mass" (p. 404-406). The concept of welding is now usually associated with the nuée ardente type of erup-

tion, and "welded tuff" is sometimes used for the depositional unit, to express the idea that it was formed by that type of eruption. But use of the term in this sense, that is, for the depositional unit, will almost always give rise to statements to the effect that a given welded tuff is nonwelded in the upper part, or, perhaps, shows no welding whatsoever. This nonsensical wording is the consequence of an unwarranted extension of a descriptive term, referring to a special manner of lithification, to a depositional unit that may be lithified by different processes and in different degrees from level to level and from place to place. "Welded tuff" will be used here in Idding's sense as a rock term, applicable to a hand specimen or a ledge, usually with qualifiers to indicate the degree of welding.

The term ignimbrite—"fire cloud rock"—was first defined by Marshall as the rock comprising a nuée ardente deposit, without regard for the degree of welding (1932, p. 200). In a later paper (1935) the term is used in this sense and also to mean the nuée ardente depositional unit, as such. It has come to be used widely in the first sense. But the pressing need, in any discussion of the stratigraphy of ancient volcanics, is for a term with Marshall's second meaning; that is, for the depositional unit formed by the nuée ardente type of eruption without regard for degree or method of lithification from level to level or from place to place. Ignimbrite is used in this sense in this paper. Actually there is no serious conflict between the two meanings, because the context usually makes it clear which is intended. "Ignimbrite" in any sense is anathema to a number of outstanding students of volcanic rocks, but it is firmly fixed in the literature, is better than any alternative term that has been proposed, and is a great deal better than a new term—like "nuée ardente" it will irritate some readers, but will confuse none.

Lateral extent.—The proposition that certain individual ignimbrites and ignimbrite sequences are regional in extent will seem to many geologists familiar with the Great Basin so patently true as to be scarcely worth stating, and to others, incredible.

Perhaps the latter attitude stems in part from the fact that our conceptions of Great Basin volcanic rocks have been based largely on studies in mining districts, where the volcanics are commonly so intensely deformed and altered by intrusions that district-wide mapping of individual depositional units is difficult or impossible (see, for example, Westgate, 1932, p. 27). Moreover, in many mining districts the volcanic section consists of lava flows, breccias and agglomerates, interlensing in disorderly fashion and laced by dikes and sills, the whole clearly an ancient volcanic pile in which many of the units change drastically in thickness and pinch out entirely within short distances. Such areas of strong deformation and alteration, and/or initial stratigraphic complexity, are the worst possible places for working out stratigraphic relationships, particularly in a suite of volcanics which did not conform to any concept of origin available at the time when most of the mining districts were mapped. Now that it is known that many ignimbrites have very great lateral extent, it is evident that the stratigraphic relationships of the volcanics can best be worked out in areas of simple structure remote from centers of intrusion and vulcanism. In many instances the firm stratigraphy thus established can then be carried

back into the areas of complexity, where the ignimbrites serve as keys to geologic problems that could not be solved locally.

Probably a much more important explanation of the general failure to recognize the usefulness of ignimbrites as regional stratigraphic units is the fact that most workers in the Great Basin have been preoccupied with other aspects of the geology, and have been inclined to dispose of the volcanics with a single map color or, if something more is required by obvious differences in lithology or structure, to lump them in the fewest possible cartographic units. An attitude that is very common in the present generation was expressed by Spurr in 1901 (p. 225):

> Our knowledge of the ranges . . . is comparatively slight, since . . . the volcanic rocks are so abundant *that nearly everywhere they mask the structure.*

The italics are mine. It goes without saying that this dim view of the volcanics is not conducive to rapid strides in the understanding of their stratigraphy. Individual depositional units are not apt to be mapped separately if it is taken to be a certainty, without looking, that they have no continuity; and the fact that many of the units are readily correlatable from range to range is not apt to be recognized if such correlation is considered to be impossible.

The literature provides some noteworthy exceptions to these generalizations. Studies by Ransome (1909) in the Goldfield district, Nevada; Ransome, Emmons, and Garrey (1910) in the Bullfrog district, Nevada; and Callaghan (1939) and Kerr and others (1957) at Marysvale, Utah, are examples of the use of Tertiary volcanic units in working out structure in mining districts of extraordinary complexity. Anderson and Russell (1939, p. 243-247) identified the Nomlaki tuff of Pliocene age in the northern Sacramento Valley as a nuée ardente deposit, and used it as a key bed in stratigraphic studies over an area of about 2000 square miles. The Rattlesnake tuff is now recognized as a single ignimbrite (Wilkinson, 1950) that may have covered as much as 5000 square miles in eastern Oregon in Pliocene time (Campbell and others, 1958). Van Houten's (1956) "vitric tuff" is a distinctive suite of Mio-Pliocene tuffaceous deposits rather than an individual depositional unit, but is is said to be recognizable and usable as a stratigraphic datum throughout most of Nevada and in neighboring parts of the Great Basin.

It is literally true that some of the volcanic units of the Iron Springs district are so distinctive lithologically, so well exposed, and so obviously continuous, that they very nearly map themselves—seven "flows" were distinguished in a reconnaissance study in 1908 (Leith and Harder, plate 1). Moreover, the volcanics are readily separable into unconformable sequences which predate and postdate the ore-bringing intrusions, and a knowledge of the detailed stratigraphy of the pre-intrusive and post-intrusive sequence is essential to any understanding of the localization of the ore bodies and virtually every other aspect of Tertiary structure and physiography. In other words, in Iron Springs it was both practicable and necessary to work with the individual depositional units comprising the volcanic section, and this work quickly changed my attitude from one close to Spurr's to the diametrically opposed position of this paper, which lumps the pre-Cambrian, Paleozoic and Mesozoic rocks as a pre-Tertiary basement complex, of interest chiefly as the underpinning of the volcanics.

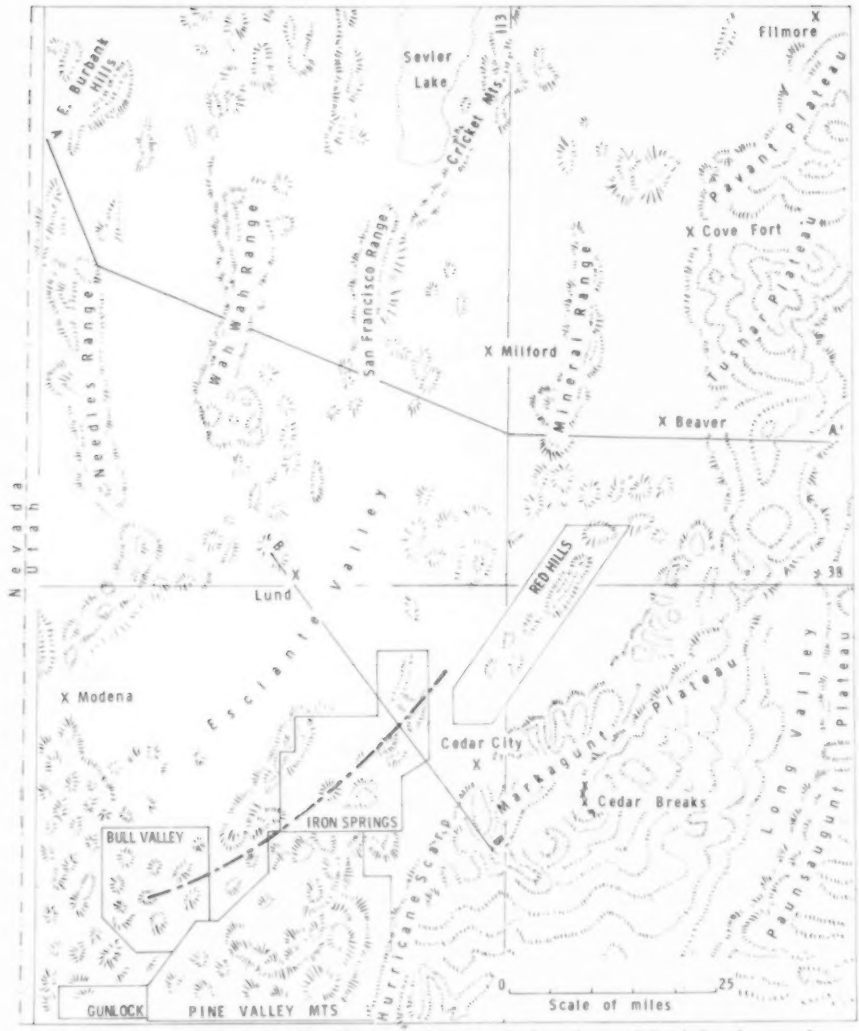

Fig. 1. Location map. The Tertiary volcanic rocks have been subdivided and mapped on a scale or 1/62,500 or larger in the districts defined by solid lines. A-A′ and B-B′ indicate the approximate location of the sketch section in figure 5 and the restored section in figure 3, respectively. The general trend of the Iron Springs Gap structure is shown by the heavy dash-dot line; this structure is greatly distorted by six intrusive bodies which are aligned along it.

An area of about 3,000 square miles centering around Iron Springs has been mapped on a scale of 1/62,500 or larger by members of the University of Washington group named earlier. With this substantial area as a proving

ground for principles of ignimbrite stratigraphy, regional reconnaissance by me indicates that an area of about 10,000 square miles in the Great Basin and the High Plateaus in southwestern Utah can be tied together by one or more groups of ignimbrites. Cook has independently developed a correlation network for an area of comparable size in eastern Nevada.

Identification of individual ignimbrites in these reconnaissance studies is based in the field on conventional lithologic characteristics and, of course, as in all correlation of stratified rocks, on similarity in sequence. A laboratory method that has proved very useful in testing tentative field correlations is outlined in an accompanying paper by Paul L. Williams. Briefly, the method involves binocular study of "thick sections", etched and stained to aid in distinguishing the minerals; ratios of crystals to ground mass, percentages of the principal rock-forming minerals, and other properties are expressed by histograms. Individually (fig. 2) or arranged in columnar sections in a correlation chart as in William's paper, the histograms provide an effective means of conveying a large amount of mineralogic data at a glance.

QUICHAPA FORMATION

General statement.—Discussion of systematic stratigraphy is beyond the scope of this article, but an understanding of the general nature of the volcanic succession and the approximate age relationships are essential for what follows. For ease of reference in this article, in the companion paper by Williams, and in other papers now in preparation by the University of Washington group, certain volcanic units that are known to be regional in extent are assigned formal stratigraphic names.

The Quichapa formation[1] is not at the base of the volcanic section in southwestern Utah, but it is in several respects well suited to introduce and illustrate the concept of a regional stratigraphy based on ignimbrites. The three or four ignimbrites comprising the formation were spread over a surface of low relief throughout most of the area where they have been mapped, and there was no roughening of any of the units by erosion prior to emplacement of the next unit. These circumstances mean (1) that the Quichapa ignimbrites show none of several sorts of internal complexities associated with strong relief on the underlying surface, and (2) that they tend to be substantially uniform in thickness and to be in the same orderly sequence over very large areas. Moreover, the Quichapa units are characterized by unique sets of lithologic features and complements of minerals that make them rather readily and positively identifiable. Finally, it so happens that the Quichapa sequence includes the three principal types of ignimbrites which occur in the Great Basin, so that most other ignimbrites can be succintly described as variants of one or another of the Quichapa units, as types.

The various makeshift names that have been used in the past for the

[1] Cook's designation of the Quichapa as a group (1957, p. 53) corresponded with my usage at that time. But in addition to the regional ignimbrites which make up most of the Quichapa, which need formal stratigraphic names, there are in many places lava flows and other local intercalations which are best referred to in lithologic terms. It is a well established rule that a formation may include undesignated units of member rank, but that all of the formations comprising a group should carry formal stratigraphic names (Ashley, 1933). Chiefly for this reason, I now favor a formational rank for the Quichapa.

TABLE 1

Comparative Nomenclature of the Volcanic Succession in Southwestern Utah

Leith and Harder, 1908	Mackin, 1954	Cook, 1957	This paper
		Page Ranch formation	Page Ranch formation: Kane Point tuff; Irontown member
		Rencher formation	Rencher formation
Succession of flows: No. 7 Biotite dacite; No. 6 Latest trachyte; No. 5 Later trachyte; No. 2 Early tuffaceous rhyolite; No. 1 Early trachyte	Volcanic rocks: Member E; Member D; Member C; Member B; Member A	Quichapa group: Tv 3; Tv 2; Tv 1	Quichapa formation: Harmony Hills tuff; Bauers tuff; Swett tuff; Leach Canyon tuff. Isom formation: Hole-in-the-Wall member; Baldhills member
			Needles Range formation: Minersville tuff; Wah Wah Springs tuff
Claron formation	Claron formation	Claron formation	Claron formation

Quichapa units, and the formal stratigraphic names that are proposed for them here and used in William's paper, are shown in table 1. The type localities, all in the Iron Springs district, are as follows: Leach Canyon tuff, the south side of Leach Canyon, Desert Mount quadrangle; Swett tuff, the west-facing scarp of the Swett Hills, Desert Mound quadrangle; Bauers tuff, Bauers Knoll, Cedar City, N. W. quadrangle; Harmony Hills tuff, the Harmony Hills, specifically, the south side of Right Quichapa Canyon, Mount Stoddard quadrangle. At these places the units are in the order of superposition shown in the table. Elsewhere in the district there are lava flows or other volcanic rocks, local in origin and extent, at every contact.

Routine descriptions of the units are given in the reports cited in table 1, and the percentages of the principal rock-forming minerals are shown by histograms in William's paper and in figure 2 of this paper. Descriptions at the type localities, given below, stress certain features of the units which bear on problems of origin.

Leach Canyon tuff.—As seen in cliff exposures in the vicinity of Leach Canyon, the Leach Canyon tuff is a single depositional unit, remarkably uni-

form in lithology through a thickness of 450-500 feet. Except at the base and near the top the rock consists of a matrix with the texture of unglazed porcelain, gray to flesh in color, enclosing fragments of dark red felsite, light gray pumice, and other rocks, and crystals of quartz, feldspar, biotite, and other pyrogenic minerals, mostly broken. A square foot of exposure commonly shows five to ten readily visible lithic fragments. The fragments make up as much as 10 percent of the rock, and the pyrogenic minerals range from 15 to 25 percent. There is no suggestion of grain-size stratification, but some favorably situated faces exhibit a poorly developed foliation paralleling the base of the unit, brought out by a preferred orientation of lenticules of pumice and other rock fragments and mineral grains. The foliation plane shows no lineation; there is no alignment of inequidimensional fragments or grains, and the pumice lenticules are shapeless blotches. The absence of lineation indicates that the foliation is a compaction structure, not a flow structure in the conventional sense.

The stony-textured material grades downward uniformly or through a zone of interlensing into black, gray, or salmon silky-lustred vitrophyre which ranges from zero to several tens of feet in thickness. The proportions and types of rock fragments and mineral grains in the vitrophyre are substantially the same as in the stony-textured material. There may or may not be a layer of pulverulant ash as much as ten feet thick at the base.

In the upper 50 to 75 feet of the unit there is a gradual decrease in the number and size of the rock fragments, and in the degree of induration. In some places the uppermost few feet consist of distinctly bedded tuff, rich in pumice granules; this part of the deposit is evidently air-fall ash. The slightly indurated upper phases are preserved only under special circumstances, to be outlined below.

The conspicuous rock fragments, the general absence of sorting, the complete gradation from basal vitrophyre to ashy top, and other characteristics of the Leach Canyon tuff indicate, on the basis of the field relations alone (without recourse to the microscope), that the unit as a whole cannot be a lava flow nor an ordinarily air fall tuff nor any combination of these; it is clearly the sort of unit for which the term "ignimbrite" was proposed by Marshall. It is in all respects closely similar to the Bishop tuff of California (Gilbert, 1938).

Bauers tuff.—The Bauers tuff differs from the Leach Canyon tuff in three ways that are of petrogenetic interest: (a) the content of pyrogenic mineral grains is appreciably lower (10 to 15 percent as compared with 15 to 25 percent); (b) foreign rock fragments are rare or absent; and (c) it is much more strongly indurated. At Bauers Knoll and in about 95 percent of its outcrop area in the Iron Springs district it consists of three intergrading but sharply contrasted phases: a basal vitrophyre about 10 feet thick; a middle lithoidal phase characterized by a conspicuous compaction foliation, 150 to 200 feet thick; and an upper non-foliated lithoidal phase, 10 to 40 feet thick.

The basal vitrophyre is black and has the glassy luster and conchoidal fracture of obsidian. Toward the top it is flecked with red spherulites. The transition to the overlying lithoidal phase is generally deeply weathered, a fact that suggests that the vitrophyre was predisposed to rapid weathering by al-

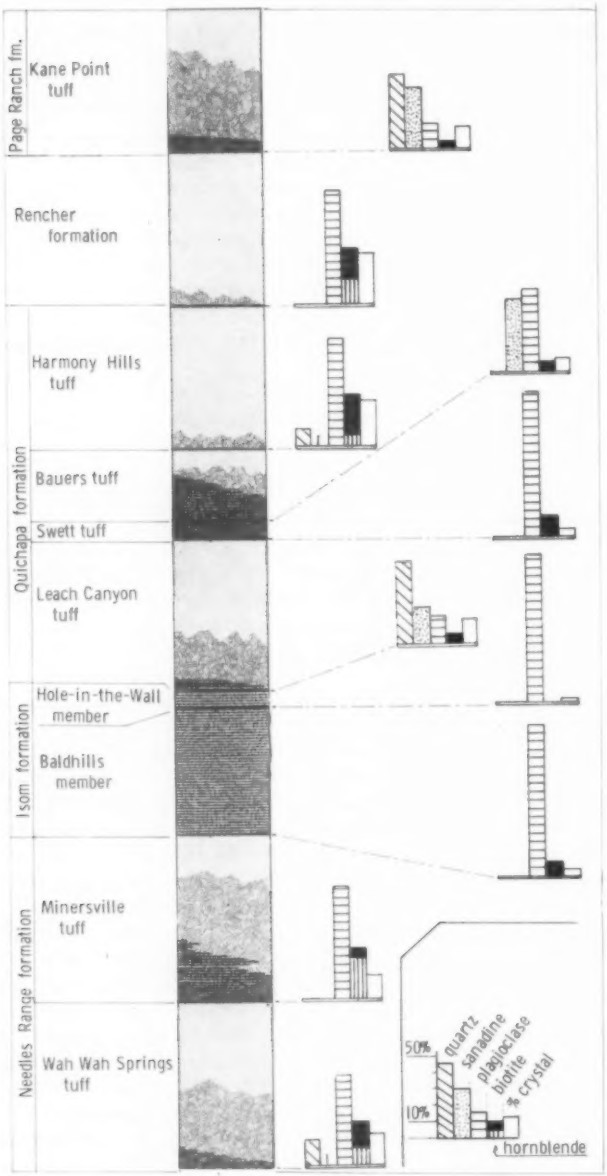

Fig. 2. Phenocryst composition of certain volcanic units.

teration effects associated with devitrification. The fact that this type of transition zone is rarely exposed explains why, in similar ignimbrites elsewhere in the Great Basin, it has been mistaken for a contact between a thin glassy lava flow and an overlying stony-textured flow or indurated pyroclastic deposit.

The foliated lithoidal phase is pale red to deep red-brown in color. The foliation is made apparent by a parallelism of light gray lenticules that make up as much as 10 percent of the rock. The lenticules range in size from barely visible wisps to 5 inches in thickness and many feet in length—the ratio of thickness to length is extremely variable, ranging from 1:2 to 1:25. The foliation tends to conform with the base of the unit and there is no lineation in the foliation plane—"length" of the lenticules, seen in a face normal to the foliation, is actually the diameter of irregular discoids. The lenticules terminate by wedging out or feathering out, or in angular faces that are suggestive of fracture but are raggedly gradational when viewed with a lens. They are in some respects superficially similar to the flattened pumice inclusions in the Leach Canyon tuff, but there is reason to believe that they were formed primarily by recrystallization of gas-rich portions of the consolidating and compacting ignimbrite material. The field and laboratory evidence bearing on this matter, and views expressed in the literature, are too involved for discussion here; it suffices to say that the gray lenticules are earmarks of the middle foliated phase of the Bauers tuff throughout its known area of distribution.

The foliated phase grades upward, usually with a decrease in depth of color, into the massive lithoidal phase which contains no lenticules. In most places the massive lithoidal phase is overlain directly by the Harmony Hills tuff; it rings to the hammer up to the contact, and the contact is knife-blade sharp, so that a specimen can be taken across it.

This relationship is anomalous. If an ignimbrite is defined as the deposit

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The vertical dimension of the columnar section is about 4000 feet; no scale is given because the section is composite, intended to convey only the general order of magnitude of the thickness of the units. All are not present in any one place. Most of the contacts are erosional disconformities and some are angular unconformities. Sedimentary and volcanic rock units of local extent, which are intercalated at every contact, are not shown.

Degree of induration is indicated schematically in the columnar section by three patterns: a light stipple for slightly indurated, friable rock; a heavy stipple for moderately indurated rock with a firm lithoidal matrix; and a heavy stipple combined with horizontal lines for vitrophyre and lithoidal rock of lava-like hardness.

The histograms are arranged in three rows corresponding with the general types of ignimbrites discussed in the text. The left column includes histograms for units of the Harmony Hills type, characterized by a relatively high percentage of crystals and a low degree of induration. The Minersville tuff, which has a very thick vitrophyre at or near the base where it is best known, is an exception to this rule. The column on the right includes the Bauers tuff and three other units of the same type, characterized by a low content of crystals and an assemblage of lithological properties indicative of high temperature at the time of emplacement; the Hole-in-the-Wall and Baldhills members may be in some manner transitional between ignimbrites and lava flows.

It should be noted that the percentages of crystals shown in the histograms includes only grains large enough for identification by binocular study of stained slices. This percentage may be considerably lower than the percentage of crystals based on study of thin sections with a petrographic microscope.

Particularly in the volcanic units with a low percentage of crystals, the phenocryst composition as shown by the histograms has little significance with regard to the rock name. For example, as noted in the text, a chemical analysis of the Baldhills member indicated that it is in the latite-quartz latite compositional range.

formed by a nuée ardente type of eruption, an ashy top should be as much a part of it as a vesicular top is a part of a lava flow. Actually the massive lithoidal phase of the Bauers tuff, only a few tens of feet thick at most, is everywhere present throughout an area of about 50 square miles mapped in detail in the Iron Springs district; there are neither erosional channels cut into or through it, nor any of the remnants of the ashy material that might be expected to survive for a long time on a flat surface in places remote from water courses. These facts count heavily against stripping away of a nonresistant top of the unit by ordinary erosional processes as an explanation of its absence.

A part of the answer is supplied by the fact that in one part of the district (the Antelope Hills) where the next overlying rock is an andesite flow, there is a complete gradation from the massive stony phase into light gray moderately indurated ash, 30 to 50 feet thick, at the top of the unit. The suggestion is that the ashy phase was elsewhere removed, not by ordinary erosion, but by hurricane sand-blasting by the nuée by which the Harmony Hills ignimbrite was formed; it was preserved only where protected by an armor of andesite flow rock. This hypothesis is supported by the fact that where the massive lithoidal phase of the Bauers ignimbrite is overlain directly by the Harmony Hills ignimbrite the knife-blade contact is itself "welded"—it is described by R. A. Christman in our field notes for 1950 as a "blow-torch contact". If the idea expressed by "blow-torch" is correct, the difference between the nature of the contact where the overlying rock is, (a) another ignimbrite and (b) a lava flow, is yet another example of the contrast that is to be anticipated between contacts in which the covering material was formed by a process (a) capable or (b) incapable of erosion (Mackin, 1950, p. 62).

The rarity of fragmental inclusions in the Bauers tuff, its conspicuous foliation, and especially its lava-like hardness from base to top where the ashy phase is missing, mean that this unit poses the field problem—lava flow or ignimbrite? The absence of lineation, implying that the foliation is a compaction structure; and the fact that this silicic rock unit is a tabular sheet of enormous areal extent, are the most obvious field criteria. Under the microscope the shard structure, and the fact that most of the mineral grains are angular fragments of crystals, are diagnostic.

Swett tuff.—The Swett tuff which underlies the Bauers tuff in the Iron Springs district (table 1) can be concisely described as a Bauers type of ignimbrite, that is, it is characterized by the same low content of mineral grains, rarity of foreign rock fragments, and a very high degree of induration. The basal vitrophyres and lithoidal phases of the two units differ in detail, but isolated specimens can be distinguished only on the basis of a mineralogic contrast (fig. 2). The Swett tuff ranges from 30 to 45 feet in thickness in the Swett Hills. Whether its absence from the section in some places in southwestern Utah is due to nondeposition or erosion is a special stratigraphic problem that needs no discussion here.

Harmony Hills tuff.—The rock composing the greater part of the Harmony Hills member is tan to light red brown in color. Grains of biotite, plagioclase, and other pyrogenic minerals make up 30 to 45 percent of the rock.

The biotite grains are cleavage flakes which tend to be oriented subparallel with the base of the unit; the resulting foliation makes it possible to obtain an attitude in most ledge outcrops. The thickness ranges from 300 to 350 feet in the Harmony Hills. It is for the most part only moderately indurated; except as noted below, there is no sign of welding. In contrast with the Bauers member, the Harmony Hills member poses the field question, ignimbrite or airfall tuff?

Perhaps the most compelling evidence bearing on this question is presence near the base of the unit of schlieren of black vitrophyre which grade into the surrounding rock, forming the "wilsonite" of the New Zealand writers (for example, Marshall, 1935, p. 330). In some places the schlieren coalesce to make a massive vitrophyre layer comparable with that of the Bauers tuff. It is significant also that most of the Harmony Hills member shows no grain size stratification—in so thick a deposit, covering an area of several thousand square miles, an absence of sorting indicates a method of spreading other than dispersal by winds.

Pock marks or nodes on some exposures of the basal part of the Harmony Hills tuff call attention to the presence of inclusions, etched out by differential weathering, which might readily escape notice on a fresh break because the lithology is similar to that of the enclosing rock. The inclusions are rounded to subangular discoids, commonly a few inches in greater diameter, oriented parallel with the base of the unit. They are clearly cognate in that they are certainly in some manner consanguineous with the rock unit in which they lie, but their mechanism of origin is uncertain and the problems are much too involved for discussion here; for the moment, the point made is that inclusions characterize the lower part of the Harmony Hills tuff in some places, and that they are autoliths rather than xenoliths.

Lateral extent of the Quichapa units.—It is a good general principle that, in the measure that an hypothesis is inherently unlikely, the evidence required to endow it with a given degree of validity must be strong in the same measure. Certainly it will seem in the highest degree unlikely to nearly everyone, perhaps "impossible" to some, that individual ignimbrites are correlatable from Brian Head (Cedar Breaks) in the Colorado Plateau for a distance of about 100 miles westward to the Upper Narrows of the White River near Hiko, Nevada. But the evidence supporting the correlation *is* very strong. We deal with three or four units, each more or less unique in mineralogy, in the same sequence in each of the histogram columnar sections in Williams' chart and in many other measured sections as well. Identity of the units is further checked by suites of heavy accessories and by special "index minerals"; for example, pan concentrates of material weathered from the Leach Canyon tuff show an amount of sphene of an altogether different order of magnitude than the content of this mineral in other ignimbrites studied to date in the Great Basin. And it should be noted that the laboratory work merely confirms correlations tentatively established in the field on the basis of general lithology, types and proportions of inclusions, jointing habits, and weathering and erosion forms of the individual ignimbrites.

The best field check of the correctness of correlation is success in prediction of the physical properties of the units next overlying and underlying the one in sight on the basis of the known succession. The Quichapa units have met this test so consistently in so many places that it is no longer surprising to find the sequence in proper order in an area examined for the first time—it is any flaw in the order that is anomalous. The explanation, if it can be worked out, is usually in terms of topographic features, residual or formed by concomitant deformation or local volcanism, which prevented the spreading of the missing unit to the place in question, or caused it to be unusually thin or thick.

The areal extent of the Quichapa formation in southwestern Utah only, that is, not including its extension in southeastern Nevada, is about 2500 square miles. A conservative average thickness of 1000 feet makes the volume about 500 cubic miles.

The Quichapa units as lithologic types.—As stated earlier, the Quichapa sequence includes representatives of the three principal types of ignimbrites which make up the Tertiary volcanic sequences in the Great Basin. Ignimbrites of the Harmony Hills type are characterized by a large percentage of pyrogenic crystals and a low degree of welding. Inclusions are typically cognate; they may be about or may make up a large share of the rock. Ignimbrites of the Bauers type are characterized by a low content of pyrogenic crystals and a high degree of welding. Inclusions are usually rare or absent. Where the vertical section is complete ignimbrites of this type commonly show the four gradational but distinct lithologic phases described above. Ignimbrites of the Leach Canyon type are intermediate between the Harmony Hills and Bauers types in content of crystals and degree of welding. Angular fragments of other rocks are usually abundant.

The foregoing paragraph fairly bristles with questions. What is meant by "degree of welding"? How can this and other properties of ignimbrites be quantified as lines of evidence bearing on such petrogenetic questions as temperature at time of emplacement? Is it a valid generalization that there is an inverse relationship between crystal content and degree of welding in the Tertiary ignimbrites, and between either or both of these properties and the nature and percentage of inclusions? If there are such relationships are the several so-called types of ignimbrite merely arbitrary divisions of one or more completely gradational sets of properties, or do the ignimbrites fall into natural groups corresponding with genetic classes? How do the sets of properties vary with differences in chemical composition? There must surely be changes in a single ignimbrite, from the vicinity of the vent to the distal margin, in temperature at the time of consolidation and also in the nature and percentages of mineral grains and inclusions; is it proper to attempt to evaluate the petrogenetic significance of differences in these properties in different ignimbrites without taking into account lateral variations in the same ignimbrite? Is there, in single eruptive episodes such as that represented by the Quichapa formation, a consistent order of occurrence of the same ignimbrite types? Do the same rules apply to sequences of ignimbrites in different parts of the Great Basin, and of different ages during the Tertiary?

These questions are worth asking because they bring out the full meaning of a point suggested earlier. We are not "drowning in data" relating to ignimbrites: we have as yet only a small fraction of the data needed for an analysis of the origin of these rock units. Work with single vertical sections, and mapping in limited areas, are good starts, but because many of the units are regional in extent, any comprehensive study of them must be on the same scale. The first step must be the restoration, as of the time of their origin, of a representative number and variety of the Tertiary ignimbrites; the evidence that is basic to such restorations can be obtained only by regional stratigraphic studies.

POST-QUICHAPA VOLCANICS

General statement.—Spreading of the Quichapa ignimbrites as flattish sheets over a tolerably level plain was followed by a protracted period during which continued or recurrent volcanism was accompanied by emplacement of laccolithic intrusions in the Iron Springs district. The intrusions produced dome mountains as much as several thousand feet high. The lowlands between and adjacent to the intrusive domes were the site of deposition of (a) direct volcanic products, as lava flows, ignimbrites and lahars, and (b) detrital materials supplied by erosion of the domes. The detrital materials consist mainly of fragments of the Quichapa and older volcanic rocks, but in some places include Tertiary and Mesozoic sedimentary rock types and fragments of intrusive rock—the sequence clearly represents the erosional deroofing of the intrusive domes. The record is complex because the direct volcanic products and the detrital materials interfinger irregularly, and especially because additional intrusions were emplaced from time to time during the period, deforming the older interintrusion trough deposits and radically changing patterns of erosion and deposition.

Rencher formation.—The Rencher formation (Cook, 1957, p. 57-59) consists predominantly of crystal ignimbrites and other volcanic rocks which may rest directly on the Harmony Hills member of the Quichapa formation, or on aprons of detritus bordering the intrusive domes, or unconformably across the truncated edges of all the older strata on the flanks of some of the domes.

Page Ranch formation.—The Rencher formation is overlain by the Page Ranch formation (Cook, 1957, p. 61-63), a composite unit typically exposed in an east-facing scarp two miles northwest of Page Ranch and one mile southwest of Old Irontown Historic Site (see Page Ranch quadrangle). The lower part of the scarp consists of crudely bedded fanglomerate, made up chiefly of subangular blocks of the Harmony Hills tuff and other Quichapa ignimbrites, here designated the Irontown member of the Page Ranch formation. The upper part of the scarp consists of a vitric ignimbrite of rhyolitic composition, here designated the Kane Point tuff for a peak of that name several miles to the southwest on the same scarp. These two members of the Page Ranch formation clearly represent the filling of a synclinal trough between the Iron Mountain and Mount Stoddard intrusions. There has been little or no deformation of the Page Ranch formation at the type locality, but elsewhere in the Iron Springs district (for example, on the east side of an intrusion that underlies parts of the Antelope Hills) it has been sharply flexed.

Age relationships.—The Leach Canyon tuff, the lowest ignimbrite of the Quichapa formation, has a zircon age of 28 m.y. (Jaffee, written communication). One of the Iron Springs intrusions (Three Peaks) is 22 m.y., and the Kane Point tuff is 19 m.y. on the same basis. These figures suggest that the Quichapa formation is Oligocene and that the Rencher-Page Ranch period of extrusive-intrusive igneous activity is late Oligocene or early Miocene.

Younger volcanics.—In the Bull Valley district a sequence of volcanics which is equivalent in part to the Page Ranch formation is overlain unconformably by a younger sequence consisting of lava flows, ignimbrites, and volcanic-derived sediments, dominantly rhyolitic in composition (oral communication, H. R. Blank). Rocks of the same lithology and position in the section are present in a number of other places in southwestern Utah (for example, the Mount Belknap rhyolite of Marysvale, Callaghan, 1939). As far as is now known, these young rhyolitic rocks postdate the emplacement of all the larger laccolithic intrusions. They differ from the older volcanics in that they are commonly associated with small plugs that were probably local feeders. While there has been as yet no attempt to work out the unit-by-unit stratigraphy of these rocks on a regional scale, there is no reason for believing that they were spread as sheets of great lateral extent, as were the older volcanics—the available evidence indicates rather that their present limited distribution corresponds approximately with their original extent. They are commonly regarded as Mio-Pliocene of Pliocene in age.

Local volcanism, chiefly the spreading of basalt flows and the building of small volcanoes, has continued through the Pleistocene into Recent time (see Gardner, 1941; Threet, 1952; Cook, 1957).

PRE-QUICHAPA VOLCANICS

Isom formation.—The Quichapa formation is underlain by a sequence of volcanics made up chiefly of ignimbrites and lava flows, with intercalations of sedimentary rocks, collectively designated the Isom formation (table 1). The type locality is the southern slope of an east-west ridge just north of Isom Creek in the northwestern part of the Iron Springs district (Three Peaks quadrangle, Sec. 5, T. 35 S., R. 12 W.). At the type locality and generally in southwestern Utah the Isom formation rests on the volcanics of the Needles Range formation (see below), but in some places it lies on the Claron formation or on older volcanic rocks of local origin. The Isom formation is as yet the least known of the volcanic sequences of southwestern Utah, both as regards its internal stratigraphy and the origin of the anomalous porphyries which characterize it; it is a complex of problems that cannot be profitably attacked until after the stratigraphy and origin of the overlying and underlying sequences have been worked out.

At the type locality the lower part of the Isom formation consists of an ignimbrite of the Leach Canyon type, a few tens of feet thick, which has not been definitely identified elsewhere and needs no formal stratigraphic name. The principal member is a sheet of porphyry of latitic composition (Leith and Harder, 1908, p. 58, analysis C), glassy to lithoidal in texture, black to dark red-brown in color, with a strong platy parting and an unusual blocky frac-

ture which causes it to break into roughly cubic granules. It is here designated the Baldhills member for its occurrence in a ridge of that name (see Three Peaks quadrangle) which trends northward from the type locality of the Isom formation. The uppermost member of the Isom formation at the type locality is a sheet of latite porphyry, lithoidal in texture and purplish gray in color, with light gray lenticules similar to those of the Bauers tuff. This unit is rarely more than 40 feet thick, but it is very widespread and is here named the Hole-in-the-Wall member for its occurrence at the east end of a pass of that name, two miles north of the type locality of the Isom formation.

The Baldhills and Hole-in-the-Wall members exhibit some of the features of ignimbrites of the very highly welded type represented by the Bauers tuff, but they have internal structural features indicative of viscous flow, and other features, as vesicules, which mark them as aberrant types. The fact that their mechnism of origin is not known does not detract from their value as stratigraphic units.

The Isom formation is at most only about 500 feet thick in the Great Basin in southwestern Utah. It thickens greatly and is widespread in the High Plateaus, but not enough is yet known of its distribution to justify an estimate of areal extent and volume.

Needles Range formation.—The Needles Range formation consists primarily of crystal-rich ignimbrites of the Harmony Hills type. Colors are commonly pink to dark red brown, but range widely from black in the solidly welded vitrophyre phases that occur near the base of some of the units to light gray in their almost incoherent uppermost parts. The type locality is the east side of the Needles Range at and south of the Garrison-Milford Highway. In this vicinity the Needles Range ignimbrites rest on an erosion surface with a local relief of as much as 500 feet cut in Paleozoic rocks, or on early Tertiary (?) fluvial and lacustrine sediments or older volcanics which lie in erosional and tectonic depressions in that surface. There is in most places no evidence of any considerable lapse of time between the deposition of these rocks and the spreading of the first ignimbrite of the Needles Range formation—the subjacent volcanics are arbitrarily excluded from the formation on the basis of lithology. In most places the Needles Range formation is sharply defined at the top by the glassy latitic rocks of the Isom formation.

Many sections of the Needles Range formation include two, and some sections include three separate ignimbrites. The lower of the two members at the type locality is here designated the Wah Wah Springs tuff, for its occurrence just south of Wah Wah Springs, fifteen miles west of the abandoned mining town of Frisco. At this place the unit is 700-800 feet thick and is probably substantially complete—it shows a complete gradation upward from a black vitrophyre at the base to a light gray nonwelded ashy top. The upper member at the type locality is designated the Minersville tuff for its occurrence in the Minersville Canyon of the Beaver River, where it is represented chiefly by dark gray to black devitrified tuff several hundred feet thick, underlain by the Wah Wah Springs tuff and overlain by the Isom formation.

Lateral variations of these and other as yet undesignated members of the Needles Range formation need no discussion here. It may be stated briefly

that crystal-rich ignimbrites believed to be parts of the Needles Range formation have been measured in many places from the Paunsaugunt Plateau north of Bryce Canyon westward 110 miles to the Nevada line; Cook (oral communication) finds that one or more of the same units are widespread in eastern Nevada. The north-south dimension is about 125 miles from the latitude of Levan to that of Cedar City. The areal extent is at least 10,000 square miles. A conservative estimate of average thickness of about 500 feet makes the volume well over 1000 cubic miles.

Stratigraphic problems.—Because the Needles Range ignimbrites are the oldest of the regional ignimbrite sheets in southwestern Utah, and because they seem to be approximately contemporaneous with the first major breakdown of the Great Basin relative to the High Plateaus, the age of the Needles Range formation is a matter of special interest. It is certainly Eocene or Oligocene, but it cannot be dated closely in this long span of time on the basis of any evidence now available to me. The following discussion is intended, not so much to establish the time range of the Needles Range formation, as to bring out the nature of certain stratigraphic problems in the Great Basin-Colorado Plateau transition zone (see caption to fig. 3), and to indicate the role of ignimbrites in the eventual solution of these problems. The discussion starts with the sedimentary Claron formation, which generally underlies the Needles Range formation in the transition zone and in the Plateau.

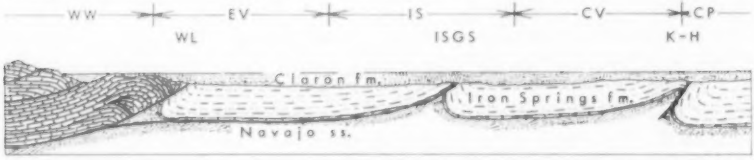

Fig. 3. Diagrammatic restored section prior to the beginning of eruptive activity.

The section trends southeastward from the southeastern part of the Wah Wah Range to the Colorado Plateau in the vicinity of Cedar City, Utah. The over-all length is about 50 miles, but the section is not to scale. WW is in the present position of the southeastern part of the Wah Wah Range; EV, Escalante Valley; IS, Iron Springs district; CV, Cedar Valley; CP, Colorado Plateau.

The major thrust which brings Paleozoic rocks over Navajo sandstone in the Wah Wah Range has been mapped by G. M. Miller (1958). It corresponds approximately in position with the so-called Wasatch Line (WL), shown by Eardley (1951, fig. 178, p. 316) as the "front of major thrust sheets" (see also Spieker, 1946, fig. 20). The principal Laramide structure in the Iron Springs district is the Iron Springs Gap structure (ISGS), a foreland décollement thrust which brings the Jurassic Carmel limestone over the Cretaceous Iron Springs sandstone; the zone of gliding is a gypsiferous horizon in the lower part of the Carmel (Mackin, 1954). At K-H the K refers to the Laramide Kanarra fold (Gregory and Williams, 1947); the H refers to the late Tertiary Hurricane fault (not shown), which follows the trend of the Kanarra fold in part of its course.

The Hurricane fault zone is the western boundary of the Colorado Plateau. The broad belt between it and the southeastern Wah Wah Range has the Mesozoic and early Tertiary stratigraphy of the Plateau, and the antithetic block fault structure of the Great Basin—it is referred to in the text as the Great Basin-Colorado Plateau transition zone. The Claron sediments were derived chiefly from Laramide thrust ranges in what is now the Wah Wah area, but were furnished in part by ridges formed by the foreland structures. The Needles Range ignimbrites were spread across the upper surface of the drawing while Claron sedimentation was still in progress in some places. The ignimbrites cannot be shown without drastic modification of the base of the drawing because the eruptions were immediately preceded or accompanied by foundering of the western part of the section.

The Claron formation consists of as much as 1500 feet of fluvial and lacustrine sediments, first described by Leith and Harder in the Iron Springs district (1908, p. 43). It is not complete at Mount Claron, but the intended rock content is clear from the Leith and Harder mapping and text treatment. In detailed remapping it is possible to carry four to seven lithologic members throughout the district (Mackin, 1954). These members need no discussion here, but are worth mention because at least three of them have exact equivalents in the Pink Cliffs at Cedar Breaks, 20 miles to the east and 5,000 feet higher, near the crest of the Markagunt Plateau. In general, both in the Iron Springs district and at Cedar Breaks the formation consists of a lower part made up chiefly of freshwater limestone, sandstone, and conglomerate, characteristically red in color, and an upper part made up chiefly of sandstone and conglomerate, characteristically light gray in color, with one or more interbedded layers of white limestone. The gray unit is increasingly tuffaceous toward the top. Gregory called the Cedar Breaks strata Wasatch or "Pink Cliffs Wasatch" and considered them to be Eocene on the basis of fresh-water shell material (1949; 1951, p. 50-52). But Claron is preferable to Wasatch as a formation name (Spieker, 1946, p. 137-139), and is used hereafter in this paper both for the Great Basin and the Plateau occurrences; "red Claron" and "gray Claron" are used informally, in much the same sense as Gregory's "red Wasatch" and "white Wasatch," for ease in reference to the lower and upper parts of the formation.[2]

In the Iron Springs and Red Hills districts the Claron formation rests on an erosion surface which truncates Cretaceous and Jurassic strata locally overturned in Laramide foreland folds (Mackin, 1954, fig. 4; Threet, 1952, p. 76-79)—the Claron is clearly post-Laramide (see fig. 3). The "red Claron" contains no igneous detritus; shards and other pyroclastic materials first appear in the "gray Claron."

Ignimbrites of the Needles Range formation rest concordantly on the "gray Claron" in an area of many hundreds of square miles in the transition zone and the Plateau. In some places, as in the northern part of the Iron Springs district, there is a lag mantle of quartzite pebbles at the contact and/or bentonitic weathering of the tuffaceous Claron sediments just below the contact. In the Red Hills and the Bull Valley districts ignimbrites that are quite certainly members of the Needles Range formation seem to be interbedded at the top of the Claron, that is, there are Claron-type sediments above, as well as below, the first Needles ignimbrites. And it may be noted that, in some places in the transition zone, volcanics similar to those which underlie the Needles Range formation at its type locality lie between the Claron formation and the Needles Range formation. The over-all relationships suggest that the explosive eruptions represented by the pre-Needles volcanics and the tuffaceous materials in the upper part of the "gray Claron" culminated in the paroxysmal nuées which spread the Needles ignimbrites across a Claron fluvial and lacustrine plain which was in some places still the site of deposition of Claron-type

[2] A paper now in preparation by Threet will explain why it is not practicable to use Gregory's "Brian Head formation" in a discussion of the detailed stratigraphy of the volcanic rocks of the High Plateaus.

sediments. This would imply that if the "gray Claron" is Eocene, the Needles Range formation is also Eocene or earliest Oligocene.

Where the Needles Range formation rests on the Claron formation in the Iron Springs district it is generally less than 100 feet thick, but in the Wah Wah Range and generally to the west, where it lies on a mature erosion surface cut in older rocks, the thickness is 1000 to 1500 feet. Because much of the nonvolcanic sediments comprising the Claron were derived from the west, it is believed that the erosional topography in the Wah Wah area must have stood above the level of the Claron depositional plain, and that it subsided immediately prior to or during the spreading of the Needles ignimbrites (fig. 3).

As shown by Threet's mapping in the Markagunt Plateau (paper in preparation) and reconnaissance by me in the Tushar and Paunsaugunt Plateaus, two or more of the units of the Claron-Needles-Isom-Quichapa sequence are seen in many sections in this southern part of the High Plateaus. These widespread units are essentially concordant in a regional sense, but they are intercalated with volcanics of local origin in many places, and where the local "volcanic piles" attained considerable height, the regional units tend to wedge out by overlap on their flanks. The stratigraphy is further complicated by erosional removal and non-deposition of some of the units as a result of local deformation. The relationships are particularly complex in the vicinity of centers of eruptive activity; in the Tushar-Marysvale eruptive area, for example, the Needles Range formation is equivalent in part of Callaghan's Bullion Canyon group (1939), and the Isom formation is equivalent in part to his Dry Hollow latite. Many unsolved stratigraphic problems need no discussion here. The point is simply that what are now the Great Basin in southwestern Utah and the southern High Plateaus were parts of a single fluvial and lacustrine depositional plain during Claron time, and continued through Needles, Isom, and part of Quichapa time to be a single volcanic field consisting chiefly of regional ignimbrites, surmounted in places by volcanoes and perhaps intrusive dome mountains. The "breakdown" along the Hurricane and related faults which made the transition zone a part of the Great Basin in topography and altitude seems to have started during Quichapa time (fig. 3).

The youngest Cretaceous sedimentary unit (the Kaiparowits formation) cut by the regional unconformity beneath the Claron is said to be Laramie in age on the basis of invertebrate and plant fossils (Gregory, 1950, p. 55-56). As indicated above, the Leach Canyon tuff has been zircon dated at 28 m.y., which tentatively places it close to the Oligocene-Miocene line of the time scale. The order of occurrence of major geologic events in southwestern Utah between these dates is reasonably well known, but the timing of the events in this long interval is not at all known. For example, it is established that the beginning of igneous activity post-dates the close of Laramide orogenic deformation in this area by a period of time long enough for erosional beveling of Laramide structures and deposition of 400 to 600 feet of nonvolcanic sediments comprising the "red Claron." The hypothesis for origin of the eruptive magmas to be presented in the sequel to this article makes the absolute length of the time interval between the main orogenic event in an area and the beginning of volcanism in the same area a matter of special interest, but because the "red Claron" is dated loosely only as Eocene, the overlying tuffaceous "gray Claron" may range from lower Eocene to middle or late Oligocene—that is, the time span between the orogeny and the eruptive activity may be a few million to as much as 30 million years. If the "gray Claron" is Green River (see below), then the question arises as to how the 20 to 30 million years that separate "gray Claron" time from Leach Canyon time should be apportioned within the Needles Range and the Isom formations, and to the "gray Claron"-Needles, Needles-Isom, and Isom-Quichapa interformational contacts. The difficulty lies in the fact that these units are regionally concordant. If the tentative dates suggested above are even approximately correct, erosional processes on the volcanic plain must have been for most of the time in a state of suspended animation which bespeaks a low altitude relative to base level.

Correlation of the Claron formation of the Pink Cliffs and southwestern Utah with the section in central Utah, where the detailed history of orogenic and early post-orogenic events has been worked out by Spieker and his Ohio State group, has long been uncertain because the intervening Marysvale-Tushar volcanic pile makes it impossible to "walk out" the sedimentary units. Spieker (1949, p. 35) and others have noted the presence of interbeds of tuff in the Green River formation of central Utah, and Muessig (1959) has presented evidence indicating that volcanism which started in Green River time culminated in the spreading of a thick pyroclastic unit which is exposed in highway cuts just south of Chicken Creek reservoir, eight miles southwest of Levan. This unit is an ignimbrite, generally similar in lithology to those of the Needles Range formation. It is overlain concordantly by Muessig's Golden Ranch formation, consisting of volcanic boulder con-

glomerate and tuffaceous sediments said to have been spread southward from the Tintic eruptive center (Muessig, 1951; Morris, 1957, p. 30). The Sage Valley limestone member of the Golden Ranch formation has yielded fossil plants regarded by R. W. Brown as upper Middle Eocene in age (Muessig, 1951). Morris states that two intrusive bodies of the Tintic eruptive center have been zircon dated as 46.5 and 38 m.y. (1957, p. 30).

Chicken Creek reservoir is several tens of miles beyond the northeastern border of the area within which the Needles Range formation is well enough known to be correlated with confidence. If the ignimbrite there is a Needles Range member then Muessig's Green River, which is gray in color and increasingly tuffaceous and bentonitic toward the top, may be equivalent in part to the "gray Claron" of southwestern Utah, which is also increasingly tuffaceous and bentonitic toward the top. The underlying Flagstaff formation, which is red in color and non-volcanic, may be equivalent to the non-volcanic "red Claron".

This general view has been held for some time by Spieker on the basis of regional stratigraphic relationships and lithologic similarities (1946, p. 136; 1949, p. 32; see also Hunt, 1956, p. 18, figs. 55 and 56). It implies that the major change from non-volcanic conditions of sedimentation to dominantly volcanic conditions occurred at about the same time in central and southwestern Utah, and that the first regional ignimbrite, a member of the Needles Range formation, spread over both areas late in Green River time.

Work by Donald P. McGookey near Richfield, in central Utah about 50 miles south of Muessig's area, indicates a different history. His section includes two volcanic units, seen in the field by me under his guidance and in company with Spieker, which are probably Needles Range and Isom members. But McGookey's Needles Range member (?) overlies a thick sequence of fluvial and lacustrine sediments, the Crazy Hollow and Gray Gulch formations, which is said to rest unconformably on the Green River formation. For this reason McGookey thinks that the Needles Range member (?) which is the first regional ignimbrite of his area is considerably younger than the ignimbrite which rests on the Green River at Chicken Creek reservoir. He suggests further, in a paper now in preparation, that the central Utah equivalents of the "red Claron" and the "gray Claron" are respectively the Crazy Hollow, which is dominantly red and non-volcanic, and the Gray Gulch, which is gray and increasingly tuffaceous toward the top. According to this view the Needles Range formation is perhaps early Oligocene in age.

It is only necessary to visualize a restored section including the sedimentary and volcanic units in question to make clear how widely varied are the possible arrangements of time lines connecting the different places, for example, the Tintic, Marysvale, and southwestern Utah eruptive centers. Analysis of the conflicting and inconclusive evidence known to me bearing on the general problem, and particularly on the age of the Needles Range formation, would not be worth the space it would occupy and it is in any case beyond the scope of this paper. The point made here is simply that (1) as emphasized by Spieker, correlation of complexly intertonguing fluvial and lacustrine sedimentary units of the type that characterize the late-orogenic and early post-orogenic period in the Colorado Plateau-Great Basin transition zone is uncertain at best and (2), when the regional stratigraphy of the volcanics has been worked out the ignimbrites will provide a means of cross-dating geologic events with a precision not obtainable by any other method.

Cross-dating establishes only the relative order of events. As indicated earlier, the ignimbrites contain enough radioactive substances to allow "absolute" age determinations within certain limits of error, which will surely be reduced as the methods are perfected.

It is interesting, after arriving laboriously at the ideas stated above, to find that Dutton's studies in the High Plateaus north and south of the Tushar volcanic pile led him to state, in 1880:

> These tufas . . . rest everywhere upon beds which are either of Bitter Creek or Green River age . . . and must have been deposited before the final dessication of the Great Eocene lake, which appears to have taken place throughout that part of its expanse now covered by the High Plateaus after the middle and before the

> close of the local Eocene. They are widely distributed and could not very probably be supposed to have accumulated in local temporary lakelets. Thus, then, the opening of the eruptive activity goes back into Eocene time (1880, p. 57).

In most places Dutton's "tufas" are ignimbrites or water-laid ash deposits belonging to the Needles Range formation.

Those interested in historical aspects of the ignimbrite concept will find delightful reading in Dutton's troubled discussion of the origin of the Needles rocks. He points out first that they could not be ordinary airfall pyroclastics because the trajectories required to explain the distance of movement of the fragments would be fantastic. More or less by default, he regards them as having been derived from erosion of older volcanics. Some well-bedded deposits in the East Fork Canyon in the Sevier Plateau are in fact stream-laid—Dutton's difficulty was with the manner of origin of intercalated units more than 100 feet thick which show no bedding or sorting. He remarks again and again the lava-like hardness of these rocks (see, for example, 1880, p. 56, 79, 244-245), and their close resemblance to lavas even under the microscope (p. 80). The hardness is credited to metamorphism (p. 245). But it is noted on the next page that they are underlain by sedimentary rocks which show "no trace of alteration." The conclusion is that the "tufas" must have been especially susceptible to metamorphism, of a type of which little is known (p. 247-248).

Summary.—The silicic volcanic rocks of the Great Basin are predominantly ignimbrites rather than lava flows. Some of the individual ignimbrites are many thousands of square miles in areal extent. They are very nearly ideal stratigraphic units in that (1) each was formed everywhere at the same instant of geologic time, (2) their upper surfaces were essentially flat when formed, and (3) they exhibit a wide variety of distinctive physical properties useful in correlation.

The eruptive activity began in southwestern Utah after the close of the Laramide orogeny, being separated from it by a period of time sufficient for (1) erosional beveling of orogenic structures developed in late Cretaceous rocks, and (2) deposition of fluvial and lacustrine sediments comprising the lower part of the Claron formation. Volcanism started late in Claron time. The same ignimbrites which overlie the Claron conformably in the Colorado Plateau are widespread in the Great Basin, where they rest directly on an erosion surface of considerable local relief cut chiefly in Paleozoic rocks. The Claron and the associated ignimbrites are considered to be post-orogenic rather than late orogenic because the deformation structures seen in these rocks are different in kind from those that characterize the orogeny.

The volcanic section in southwestern Utah consists of (1) a Needles-Isom sequence, perhaps Eocene or early Oligocene in age, (2) a Quichapa-Page Ranch sequence, of perhaps Oligo-Miocene age, and (3) an unnamed sequence of late Tertiary rhyolite flows and pyroclastic units. Correlation with other parts of the Great Basin and the Colorado Plateau is as yet uncertain, but enough is known to make it evident that it will be possible to establish an ignimbrite stratigraphy for the Tertiary on a regional scale.

Questions that will be automatically resolved by the regional stratigraphic approach are (1) location of vent areas and (2) whether episodes of eruptive

activity in the various parts of the Great Basin were contemporaneous, or were otherwise systematically or randomly placed in time. The ignimbrite stratigraphy will provide a much-needed basis for working out the post-orogenic deformational history of the Great Basin, to be considered in the next section. Finally, a well-established regional stratigraphy is a prerequisite for obtaining data on lateral and vertical variations in thickness, degree of welding, sizes of crystals and clasts, and other original features of ignimbrites, that are essential to any understanding of the origin of these extraordinary volcanic units.

THE BASIN-RANGE PROBLEM

The physiographic approach.—The history of thought regarding the origin of basin-range topography has been summarized by Davis (1903, 1905), Gilbert (1928), and most comprehensively, with respect to its stratigraphic and structural aspects, by Nolan (1943); the high points that are significant for present purposes can be stated very briefly:

King stated (1870) that the present topography was formed by erosion of highlands produced initially by the deformation recorded by structures of the pre-Tertiary rocks comprising the ranges. This view is representative of the habits of thought current at that time, as exemplified by the theory held by the Rogers brothers and Lesley for the origin of the Appalachian Mountains. The deformational history of an area was interpreted solely on the basis of the structures of the rocks—landforms entered into the thinking only as indicating the recency or antiquity of the orogeny.

Gilbert (1874, 1875) saw a difference in kind between the narrow, V-shaped erosional valleys that dissect the ranges and the broad alluvium-floored basins that lie between them. He noted, moreover, that the trend of the ranges commonly differs from the trend of their internal structures, and that at many range fronts the structures are truncated by straight baselines not adequately explained by erosion alone. He concluded from these and other physiographic relationships that the ranges must correspond with blocks raised relative to the adjoining basin blocks by movement on range-front faults. Powell (1877), and at about the same time King (1878), recognized the possibility of two distinctly different types of crustal movements in the Great Basin, and Powell especially made the point that the folds and other strongly compressional structures within the ranges pre-date and must have been deeply eroded prior to the block faulting. Dutton (1880, p. 48) stated this view succinctly:

> These flexures are not, so far as can be discerned, associated with the building of the existing mountains in such a manner as to justify the inference that the flexing and the rearing of the ranges are correlatively associated. On the contrary, the flexures are in the main older than the mountains, and the mountains were blocked out by faults from a platform which had been plicated long before, and after the inequalities due to such pre-existing flexures had been nearly obliterated by erosion.

In opposition to these views, Spurr (1901) pointed out (1) that many high-angle faults within the ranges have no topographic expression, and (2) that there are no faults at many range fronts, where the alluvial deposits of the valleys overlap on the range-forming rocks. He made it clear that he depended on the solid geology that could be seen in a ledge and beaten with a hammer,

not on landforms: on this basis he insisted that the existing topography could be accounted for by erosion of folds, without benefit of later block faulting.

In reply to Spurr, Davis (1903, 1905) defended the Gilbert concept and developed the physiographic criteria for block faulting in the form now found in most geologic textbooks. With his usual perception for essentials he outlined the geologic history of the Great Basin in terms of (a) growth of an ancestral range of *King Mountains* during the Laramide orogeny, (b) reduction of these mountains to the *Powell Plain* in early Tertiary time, and (c) subsequent formation of the *Gilbert Ranges* by block faulting (Davis, 1930).

If to the many oversimplifications of the last two paragraphs one more is added to the effect that block faulting began or occurred chiefly in late Cenozoic time, then we have the version of the basin-range theory expressed by the familiar Davis diagram showing a tilted block consisting of folded strata, bounded on one or both sides by faults, in process of burial by upbuilding basin fills of its own detritus. This picture may be thought of as representing the general consensus at the end of the heroic period—the Gilbert-Powell-Dutton period—of development of the basin-range concept. It is difficult, looking back over the years, to grasp fully the impact of the new, much needed, and obviously good idea which was the crux of that concept, i.e., that the origin of a range as a topographic feature may be an entirely different matter from the origin of its internal structures.

The development of the concept in this century is marked by an increasing awareness that the first-cycle block-fault range is only one of a variety of range types that occur in the Great Basin. Marked contrast in the stages of erosional development of different ranges was recognized early by Davis (1905, see also 1925) as indicating differences in the date of faulting from place to place. The graded slopes extending basinward from many ranges were definitely identified as pediments rather than alluvial fans; that is, as erosion surfaces cut in the range-forming rock or in Tertiary fluvial and lacustrine deposits which accumulated under topographic conditions wholly different from those of the present. Blackwelder (1928) led the way in constructive criticism of the one-cycle version of the concept, emphasizing the need for discriminating between fault scarps and fault-line scarps which, while superficially similar to each other in form, are wholly different in geologic meaning. Representative of the attainment of maturity in our understanding of the significance of landforms with regard to the Tertiary deformational history are Nolan's review of the literature (1943) and many recent papers dealing with individual ranges (for example, Sharp, 1939).

The structural approach.—The physiographic criteria for block faulting apply to best advantage in ranges in an early stage of erosional development—the morphologic features indicative of faulting are quickly blurred and may be lost altogether in ranges that have advanced beyond early maturity. This means that, insofar as topographic form is concerned, the more deeply eroded ranges might as well be Tertiary anticlines as Tertiary fault blocks. It means, also, if commonly held rates of erosion are accepted as true, that there can be no topographic evidence of early Tertiary deformation—perhaps this point lies

behind the idea that Great Basin block faulting occurred chiefly during the late Tertiary.

Even in those ranges where it is well preserved, the "pre-faulting" erosion surface can be used for measurement of block tilting and fault displacement only in very general terms because it was in most places a surface of considerable local relief (see, for example, Eardley, 1933). And there is always a question as to whether the "pre-faulting" surface is a "Powell Surface" in the sense of Davis' meaning, that is, an erosion surface which pre-dates the beginning of block faulting, or whether it may have been developed during a period of relative crustal quiet between two episodes of block faulting. The difficulty in dealing with the deformational and erosional history of a Great Basin range in quantitative terms on the basis of a restoration of the "pre-faulting" erosion surface is brought out clearly by Gilluly's sensitive handling of the problem in the Oquirrh Range (1928, p. 120-122).

Structural and stratigraphic evidences of block faulting which are at least in principle free from these limitations were described by Russell (1884) in southern Oregon, where Steens Mountain and other ranges consist mainly of mid-Tertiary basalt. The ranges are sharply asymmetric in form. The gentle "back-slopes" correspond approximately with the homoclinal dip of the basalt, and the scarp slopes in many places show complex structures, generally credited to step faulting, drag effects, or superficial slides. There has been question as to whether the main faulting is reverse or normal (Smith, 1927; Fuller and Waters, 1929) and there is a possibility that some of the ranges are asymmetric anticlines (personal communication, Harry Wheeler). Definite answers await detailed mapping based on unit by unit stratigraphy of the volcanics.

Figure 4, a section of Umtanum Ridge in Central Washington, brings out the point that asymmetry of form coupled with homoclinal structure in a ridge formed by uplift does not necessarily mean that the ridge is a fault block. The structure of the north side of Umtanum Ridge is excellently exposed where the

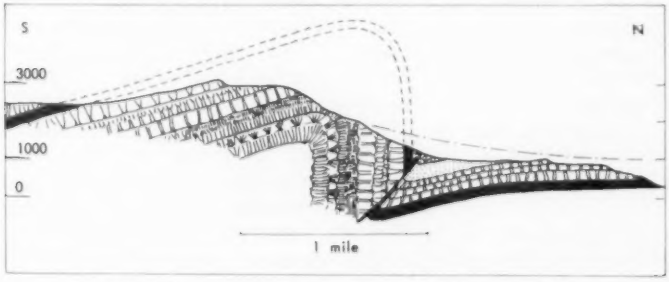

Fig. 4. Diagrammatic structure section of Umtanum Ridge.
The section is located just west of the Columbia River near Priest Rapids, Washington. The flows are part of the Yakima Basalt, of late Miocene age. The section includes twelve stratigraphic units that are rapidly mappable throughout this part of the Columbia Basin. The unit shown in solid black below the surface and restored by dotted lines above the surface is a widespread porphyritic flow, distinguished in the drawing to bring out the structural relationships. The dash-dot line indicates the approximate level and form of a pediment which bevels the steep limb of the fold in places remote from the main drainage lines. Where the pediment is covered by alluvium, the ridge simulates a tilted fault block.

Columbia River cuts across it diagonally. The flows and interbeds shown are good cartographic units (Mackin, 1955). The structure is a fold, overturned and overthrust to the north. Where this and other similar structures in Central Washington are remote from main streams the shattered basalt of the steep limb is commonly truncated by a pediment (Waters, 1955, p. 676-679) and the topographic high is on the gently dipping limb as much as a mile from the surface trace of the axial plane of the fold. The nature of the structure is apparent in most places because the pediments are in various stages of dissection, but if the lowlands were completely veneered by alluvium, the topographic from and homoclinal structure of the ridge might well be taken to mean that it is a tilted fault block. The Columbia Basin is, of course, an altogether different structural province from the Great Basin, but an image of Umtanum Ridge, as it would appear if the drainage happened to be internal, is a salutary item in the mental equipment of anyone dealing with the basin-range problem in the Great Basin.

Louderback (1904, 1923) is properly credited with bringing structural evidence afforded by Tertiary rocks, chiefly volcanics, to bear on the origin of typical Great Basin ranges in northwestern Nevada. Davis (1930, p. 299) made "louderback" a specific name for an erosion remnant of a lava flow on the back slope of a tilted fault block consisting primarily of complexly-structured pre-Tertiary rocks. The advantage of the tilted flow (the structural approach) relative to the tilted erosion surface (the physiographic approach) lies in the fact that it is planar—if the "louderback" flow is exposed at a low altitude adjacent to the range front it provides a means, not only of proving the general nature of the deformation, but of measuring it very closely (fig. 6). Moreover remnants of the flow may remain as structural evidence of block faulting long after the range has been beveled by erosion. The particular points made here are (1) that ignimbrites are available throughout much of the Great Basin to serve in the role of louderbacks, and (2) that they are widespread sheets susceptible to the regional stratigraphic approach.

Illustrations of basin-range structure.—Figure 5A is a diagrammatic section across several ranges in southwestern Utah, not along any straight line, but offset to transect the ranges where the structural relationships of the volcanic rocks are most clearly seen. The approximate latitude of the section was determined by the fact that the volcanics thicken markedly southward in each of the ranges until the pre-Tertiary rocks are lost to sight, and thin northward until erosion remnants of this sequence of volcanics are so scattered that they do not provide a structural picture. The relationships shown in the section are based on stratigraphic reconnaissance in which the principal concern was with measurement of sections rather than with areal or structural geology as such. Much remains to be learned about the structure, and the stratigraphy as well, but the essential relationships in figure 5 are well established.

The first of these is that the Needles Range formation was originally continuous throughout the area of the section. This conclusion is based on the fact that the two principal members of the formation (the Wah Wah Springs tuff and the Minersville tuff), and certain members of the overlying Isom formation, are definitely correlatable from range to range. Residual peaks of older

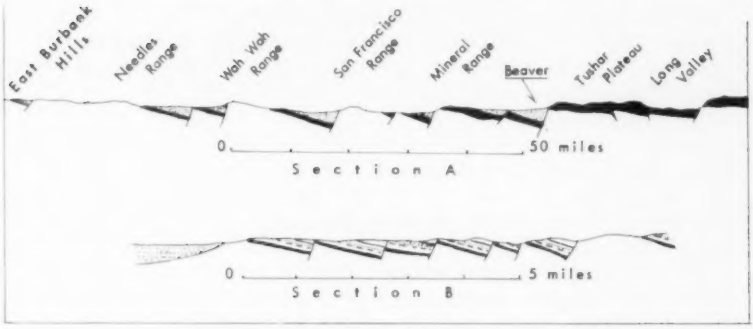

Fig. 5. Diagrammatic structure sections in southwestern Utah.

Section A extends southeastward from Garrison near the Nevada line to Beaver, Utah, and thence eastward into the Colorado Plateau. The Tertiary volcanic rocks, shown in solid black, rest mainly on Paleozoic rocks in the western half of the section, and mainly on the Claron formation in the eastern half (see fig. 3). In the Needles and Wah Wah ranges the Needles Range formation is 0-500 feet thick and makes up most of the volcanic sequence. It thickens eastward to 1000-1500 feet in the Tushar Plateau, but the marked increase in thickness shown diagramatically in the section is due chiefly to the fact that, in the Tushar area, it is overlain by thick Isom units and by several thousand feet of post-Isom flows and pyroclastics. The east-dipping homoclinal structure that characterizes the volcanic rocks in the Needles, Wah Wah, San Francisco, and Mineral ranges is greatly distorted in parts of the San Francisco and Mineral ranges by Tertiary intrusions; the intrusions, and their structural effects, are not shown. Faulting began in Needles time or earlier, but most of the faulting that controls the topography is middle or late Tertiary.

Section B passes east-west through the southern part of the Mineral Range, three to five miles south of the Beaver River. The sequence consists of Needles, Isom, and lower Quichapa ignimbrites, interbedded with lava flows and lahars from the Tushar eruptive center. The unit shown in solid black is a member of the Isom formation.

rock may have protruded through the volcanics, and there is reason to believe that block faulting was in progress in some places during Needles time, but the similarity in the volcanic sequence from range to range indicates that the Needles nuées ardentes swept across the entire span of the section.

The interpretation shown in the section, which makes each range a tilted fault block bounded by normal faults, is the traditional basin-range theory, clearly exemplified by Butler's sections of the San Francisco Mountains and the adjoining ranges (1913; 1920, figs. 2 and 53). It could be argued, because not a single range-front fault is exposed, that the faults might just as well be reverse as normal, or for that matter, that the Tertiary structure might be drawn as a series of asymmetric folds of the Umtanum Ridge type, with the steep western limbs of the anticlines nowhere exposed.

Perhaps the most direct objection to the fold hypothesis is simply that, if there were in fact western limbs consisting of volcanic rocks, these *should* be exposed somewhere, in so many ranges, at, or north or south of, the line of section. Circumstantial evidence bearing on the question is as follows:

Section B in figure 5 is an east-west section through the South Mineral Range (the Mineral Range south of the Beaver River). The volcanic strata dip eastward in a belt four to six miles wide. If the faults were not recognized, the section could be taken to mean a thickness of the order of 10,000 feet. Actually

it includes distinctive units that are repeated as many as five times—the thickness is less than 2,000 feet. The faults branch and rejoin, so that their number, and the stratigraphy of the fault blocks, varies considerably along the strike. This pattern relationship, the stratigraphy of the volcanic rocks, and the fact that there are generally no reversals in dip in these rocks, prove that the structure within this range cannot be a system of asymmetric folds. Gilbert's conclusion, based primarily on morphology, that basin-range deformation was by fault displacement of "comparatively rigid bodies of strata" (1874, p. 48) is borne out by the fact that the characteristic structure in the Tertiary volcanic rocks, whatever the scale, is the homocline—the tilted slab bounded by faults.

The dip of only a small percentage of the faults in the South Mineral Range is ascertainable. Of these, most are high angle normal and a few are high angle reverse. If structures due to intrusion and other non-tectonic causes are for the moment left out of account, normal faulting is the rule and reverse faulting the exception in the Tertiary volcanic rocks within the ranges in southwestern Utah. Gilbert's generalization that range-front faults probably have the same geometry as faults within the ranges, and are therefore probably normal holds true for the few range front faults in southwestern Utah for which attitudes have been determined, and for other places in the Great Basin where special attention has been directed to this problem (see, for example, Gilluly, 1928, p. 1113-1116).

If one word expresses the habit of basin-range faulting more completely than any other, it is "antithetic," in the sense that, regardless of the direction of the dip of the faults, their throws tend to be opposite to, and to counteract the effect of, the dip of the faulted strata (fig. 5). Perhaps the best way to grasp how firmly fixed is this habit is the hard way, by being repeatedly rebuffed by repetition of the same units, again and again, in measurement of a great many sections of homoclinally dipping volcanics; antithetic faulting is so common that in measuring sections it should be assumed to be present unless proven to be absent. The ranges themselves tend to form antithetic groups; that is, the direction of tilt is commonly not reversed from range to range, but tends to remain the same for a small number of ranges, and then to be in the opposite direction for the next small number. This relationship is seen in nearly every traverse across the range trends. Any theory of origin of basin-range structure must take it into account.

A generalized east-west section from the Toquima Range in central Nevada to the House Range in Utah, in a paper by John Osmond (in press) came to my attention after this article was substantially completed. Osmond's section is similar to those in figure 5 in that the direction of tilt of each of the thirteen ranges shown in it is indicated diagrammatically by a thick black dash representing a sheet of "early Tertiary" volcanic rock; it differs in that the direction of tilt is more frequently reversed. The tilt directions can be expressed by a formula in which E and W, meaning eastward and westward, are coupled with integers for the number of ranges inclined in each direction. For Osmond's section this is, from west to east: 2W, 3E, 2W, 1E, 2E, 1W, 1E.

There is, of course, no *a priori* reason why some of the ranges of the Great Basin should not be Tertiary anticlinal folds rather than fault blocks.

The chief reason for thinking that none were formed by folding is simply that no unequivocal cases have been described. Unequivocal means after elimination of (1) drag folds and other structures formed by draping of Tertiary strata over fault blocks, (2) local folding due to jamming between blocks, and (3) arching and compressional folding around intrusions, and other pseudotectonic effects to be considered later.

It goes without saying that Tertiary strata are needed to demonstrate a Tertiary fold. The fact that a range corresponds with an anticlinal structure in Paleozoic rocks cannot be taken as proof that the range as a topographic feature is a Tertiary anticline unless it can be demonstrated that the Paleozoic strata remained flat until folded during the Tertiary. If the anticlinal structure is defined by a thrust plane it must be demonstrated, in addition (1) that the thrust was nearly flat when it was formed, and (2) that it was not folded during the waning stages of the orogeny in which it was formed or during subsequent periods of pre-Tertiary compressive deformation. In attempting to show that the ranges of the Great Basin were formed by erosion (not by faulting), Spurr (1901, p. 219-240) proved that the structure of the pre-Tertiary rocks has no direct bearing on the origin of the ranges by simply pointing out that the number of ranges showing anticlinal structure in pre-Tertiary rocks is equaled or exceeded by the number in which the structure is synclinal. What is more compelling, most ranges are neither anticlinal nor synclinal but, to the extent that they consist of folded strata, are both from place to place because the trend of the fold axes is diagonal to the trend of the ranges. Finally, and most compelling, is the line of evidence mentioned earlier; namely, that Tertiary volcanic rocks, characterized by simple homoclinal structure, commonly rest on an unconformity which bevels the edges of compressional structures developed in the pre-Tertiary rocks. Some of the ranges in Osmond's section bring out this point very clearly, and the list of examples could be greatly extended if there were any point in so doing. The most recently described and most striking example known to me is the case of the Stansbury Mountains in Utah; the structure of the pre-Tertiary rocks is anticlinal, but the range is shown by Rigby (1958) to be a Tertiary fault block on the basis of physiographic relationships and the structure of scattered erosion remnants of Tertiary volcanics.

Spurr credits the homoclinal structure of Tertiary rocks to folding unless there is conclusive evidence that it was formed by faulting. It is of course true that, if the intervening basin floor is concealed by alluvium, adjacent ranges in which Tertiary rocks dip in opposite directions can be interpreted either as limbs of a single fold, or as a pair of oppositely tilted fault blocks, *provided* (a) *that attention is limited to a single cross-section, not to the arrangement of the ranges in plan and* (b) *that this cross-section is viewed out of the context of its regional setting.*

Opposed dips in adjacent ridges in the Pennsylvania Appalachians can be confidently interpreted as limbs of a fold even though the structure of the intervening valley is concealed, because (1) the axial parts of the many folds are excellently exposed throughout the Pennsylvania Ridge and Valley province; (2) the two ridges and the valley in question are elements of a systematic

map pattern that is uniquely associated with plunging folds; and (3) drag folds, fracture cleavage, and other internal structures in both ridges indicate strain relationships known to be characteristic of the limbs of folds. But in the Great Basin all three lines of evidence indicate that block faulting, not folding, was the general habit of deformation during the Tertiary.

This is *not* to say that there was no folding anywhere, nor at any time. It means, rather, that evidence of folding merits special attention; a question certain to be encountered very early in any inquiry into the origin of basin-range structure is whether the kind of stress condition manifested by dip-slip movements on faults inclined 60° to 70°, which was surely the "normal" stress condition in the Great Basin, was reversed by one or more episodes of apparent crustal shortening during the Tertiary. But it means also that the "burden of proof" is on Tertiary folding as an interpretation of geologic elements that are equally well explained by Tertiary block faulting and/or pre-Tertiary folding —something more than opposed dips is needed to prove a Tertiary fold in the Great Basin.

Structure and topographic form.—Figure 6 serves as a basis for discussion of the timing of basin-range movements in southwestern Utah. The volcanic unit shown in solid black in diagram A is supposed to have been spread over

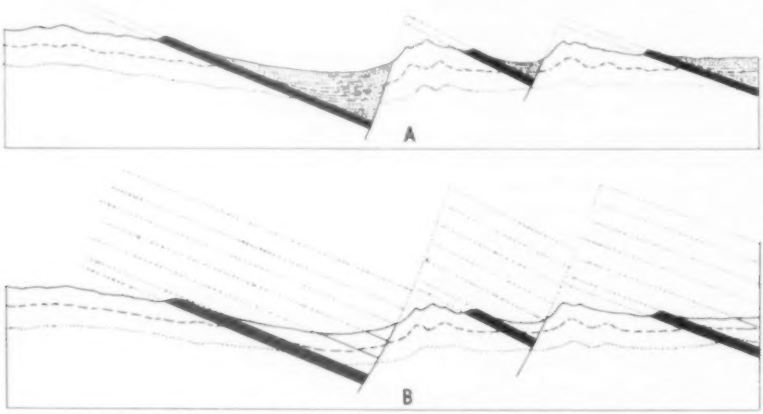

Fig. 6. Relationships between structure and topographic form.

the area just prior to the block faulting. The basins are occupied by playa lakes and are in process of filling by detritus washed in from first-cycle ranges. That the ranges are tilted fault blocks would be suspected on the basis of topographic form alone even if there were no volcanic rocks, but as indicated earlier the presence of the volcanics, and especially the knowledge that the several occurrences are parts of an originally continuous sheet, make it possible to work out the erosional and deformational histories in a degree of refinement that could not otherwise be attained.

The dashed line indicates a later stage of erosional development, produced with respect to baselevel at some remote place, such as a lower playa or

the sea. The basin floors are pediments cut in the earlier fill, and the range front in the center of the drawing is a resurrected fault scarp. The dotted line indicates a still later erosional stage, with the ranges reduced to low relief. In the stages represented by the dashed and dotted lines the principal, and perhaps the only evidence of the episode of block faulting is the structure of the volcanic rocks.

Diagram B is similar to A except that the volcanic unit is overlain by a thick sequence of weak sediments deposited prior to the faulting. All the profiles, solid, dashed, and dotted, are entirely erosional. There are probably no simple, large-scale examples of this case as such, but tilted sedimentary sequences deposited under conditions wholly different from those of the present time are common in some parts of the Great Basin.

A common variant of these histories is the spreading of a younger sequence of volcanics across the erosion surface in any erosional stage in either diagram followed by a second episode of block faulting, on the same faults or new ones, and with the same or the opposite direction of block tilting.

The precipitous Hurricane scarp in the latitude of Kanarraville, Utah (Gardner, 1941), is analogous to the fault scarp in figure 6. The fact that the Eocene (?) Claron formation and the Oligocene (?) Leach Canyon tuff are substantially conformable in the Plateau and the Great Basin indicates that probably no major movement on the Hurricane fault occurred during the early Tertiary. Movement started during the mid-Tertiary and continues to the present. The same conclusion applies to many other scarps in the Great Basin.

At the other extreme are extensive areas where there is basin-range structure but no basin-range topography. In the East Burbank Hills, for example, wide-spaced erosion remnants of the Needles Range formation represent the deeply inset edges of tilted fault blocks, preserved in what is now a late mature landscape (fig. 5A). The relationships are analogous to those shown by dashed and dotted lines in figure 6. The faulting is certainly much older than that in the Hurricane zone—the advanced erosional stage suggests that it probably occurred during the early Tertiary, with little or no reactivation during the late Tertiary. And the subdued erosional topography of the East Burbank Hills, which passes beneath the surrounding alluvium with a contact that is irregular in plan and generally shows no break in slope, is overlooked on the west by the rugged and straight-based front of the Snake Range, credited by Drewes (1958, p. 237-238) to normal faulting of as much as 7,000 feet during middle and late Tertiary time.

Two or more episodes of normal faulting are demonstrated by structure, stratigraphy, and relationships of the faults to intrusions and metallization in many places in the Great Basin (see, for example, Ferguson, 1924; Hewett, 1931; Gianella, 1936).

Finally, some areas, for example, the greater part of the Iron Springs district show little or no evidence of block faulting even though there are volcanic rocks of several ages to record such movements.

The fact that Great Basin block faulting may have no topographic expression raises a question as to whether "basin-range structure" should be re-

stricted to what seems to have been its original meaning, i.e., the block fault structure that produced the present ranges,[3] or whether it should be explicitly broadened to conform with what it means to most people working in the Great Basin, i.e., Cenozoic block faulting without regard for the relationship of the faulting to topographic form. It is used in the latter sense throughout this paper.

Summary.—Gilbert and his colleagues concluded on physiographic grounds that the relief features formed by orogenic deformation in what is now the Great Basin area were reduced by erosion to a surface of moderate relief, and that the present Basin ranges were formed by block faulting. This fundamental distinction between orogenic and post-orogenic stages of deformation was established early in the investigation of the geology of the Colorado Plateau, where the early Tertiary Claron is clearly unconformable across the great east-throwing Laramide monoclines but is displaced by the west-throwing Tertiary faults. In the Plateau-Great Basin transition zone in southwestern Utah the Claron lies on an erosion surface which bevels foreland folds and thrusts developed in late Cretaceous and older rocks, and is itself involved in typical Great Basin antithetic block faulting. In the Great Basin to the west, the Claron is not present as a continuous sedimentary deposit, but the ignimbrites which are conformable with it in the Plateau and the transition zone serve the same critical role, namely, as stratigraphic units that were spread as flat sheets across the stumps of the orogenic structures, and therefore provide a record of post-orogenic deformation. The ignimbrites confirm the Gilbert-Davis view that the Basin ranges were formed by block faulting.

More specifically, the ignimbrites permit a working out of the geometry of the Great Basin block-fault type of deformation with a precision that would not otherwise be possible. And because they range in age throughout much of the Tertiary and are virtually ideal time-stratigraphic units, they provide a key (a) to such problems as whether the block faulting has been episodic in a regional sense or random in distribution in space and time, (b) to the relationship of the block faulting to eruptive activity, and (c) to many other elements of the geologic history that are essential to any understanding of the mechanism of deformation.

INTRUSIONS AS "STRUCTURE-MAKERS"

Antithetic faulting associated with intrusions of low structural relief.—The topography and exposed geology in figure 7, if encountered in the field in the Great Basin—without benefit of the subsurface relationships shown in the section—might well be taken to mean that the alluvium-floored basin is under-

[3] It is interesting to note that "basin-range" was not, to Gilbert, a contraction of *ranges* and the intervening alluviated *basins*, but a designation of a member of the system of the Ranges of the (Great) Basin. Basin-range structure is the fault block structure believed by Gilbert to be characteristic of the Great Basin. He states (1928, p. 1):

> If with the advance of knowledge geologists shall conclude the fault block structure is not the dominant structure of the Basin Range, the term Basin Range structure can no longer be used in its original sense and may properly be abandoned.

For use as an adjective it is preferable to reduce the capital letter to lower case, and it makes for clarity if the words are hyphenated, i.e., basin-range topography.

lain by a down-faulted block consisting of the same volcanic rock units which form the ranges on either side. The fact that the volcanic rocks stand highest along the borders of the basin, and dip away from it, might be construed as evidence that the faulting is of the ramp type—that is, that the major faults are thrusts which curve back under the ranges (Willis, 1928, p. 510-537). The minor normal faults exposed along the scarps would then be regarded as superficial slips. But if the same relationships were viewed through glasses of a different color, the normal faults might be seen as the principal structural elements or symptomatic of them, and the ranges might appear as tilted blocks in a setting of regional "tension."

How little the topography and exposed geology justify either of these views can be brought out by considering some elementary physiographic reasoning, and by additional items of information as to the subsurface geology of the basin floor.

If throughout its course each of the paired scarps corresponds with a resistant-over-weak-rock relationship, and if the graded slopes are everywhere alluvium-veneered pediments rather than aggradational surfaces, then the topography is fully accounted for by differential erosion and cannot be considered evidence of block faulting. The point is worth making because this topographic relationship—the broad, flattish-floored basin flanked by rugged ranges with straight base lines—tends to be associated with basin-range structure even though both Gilbert and Davis were careful to point out that the physiographic criteria for block faulting do *not* apply to the case shown in figure 7. But the association is so strong that the step faults along the range-fronts tend to clinch the case for block faulting.

It would take only a few strategically located exposures, revealing that the sub-alluvium floor across the entire width of the basin consists of the weak sedimentary rock which underlies the scarp-forming strata, to eliminate block faulting as an essential element in the geologic history. These exposures would indicate that the structure is an arch, deroofed by erosion, with inversion of relief because the axial area at this level is composed of weak rock.

Depending on the color of the glasses through which the arch is viewed, it may be seen as a compressional anticline, proof positive of crustal shortening subsequent to the spreading of the Tertiary volcanics. It might seem that the normal faults in both limbs would give pause to this view. But if the coloring of the glasses is deep enough the faults are seen, not as anomalous structures, but as evidence of a period of relaxation after the period of compression, or as evidence that there have been periods of crustal shortening and lengthening from time to time during the Tertiary.

Because he can look deeper than the floor of the basin, the reader has been aware all along that the structure in figure 7 is an intrusive arch. The model for the drawing is the Neck of the Desert, an alluvium-floored lowland in the Iron Springs district. The lowland and the bordering ranges are superficially similar to basin-range topography, but the scarps are actually cuesta faces, kept steep and straight by sapping—they are clearly in Dutton's department, rather than Gilbert's. The presence of a concordant intrusion at depth is proved

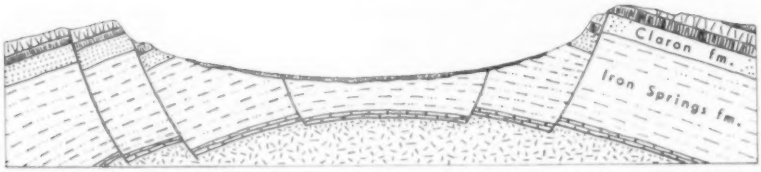

Fig. 7. Diagrammatic section across "The Neck of the Desert," Iron Springs district, Utah. The vertical scale is exaggerated—the valley floor is four to six miles wide and the total relief is only about 1000 feet. The fact that the graded slopes at the base of the scarps are pediments, rather than the surfaces of thick alluvial fills occupying a graben, indicates that the step faults in the vicinity of the scarps could not have been formed by "gravity sliding" from faces oversteepened by rapid uplifting movements on major faults which are now concealed. The possibility that some of the tilted blocks at the base of the scarps may be Toreva-type blocks, slumped from faces oversteepened by sapping, cannot be eliminated by field evidence in every instance. But the fact that the same types of antithetic faults occur in many places remote from scarps indicates that this type of "lengthening fault" is indigenous in the stretched roofs of intrusions of low structural relief.

by drilling for iron ore which occurs as replacement pods at the intrusive contact.

This type of structure—the intrusive arch or dome—is seen in southwestern Utah in every stage of erosional development from (1) the unbreached arch of volcanics; through (2) the first topographic reversal, the erosional lowland on the Cretaceous; to (3) the second topographic reversal, the mountain mass formed by the resistant intrusive rock. Excellent exposures at all erosional levels make it evident that antithetic normal faults of the type shown in figure 7, which have been variously misinterpreted in the foregoing discussion, are in fact commonplace structures in the stretched roofs of the Iron Springs intrusions (Mackin, 1954, fig. 4). They are members of the family of "roof-lengthening" faults (streckflächen) of the Cloos school, observed in many intrusions (see, for examples, Balk, 1937; Robinson, 1913, fig. 23) and beautifully developed in the model studies of Hans Cloos (1939). Their arrangement in the intrusive arches and domes of Iron Springs is strikingly similar to that developed above salt domes on the Gulf Coast (Wallace, 1944) and "salt anticlines" of the Colorado Plateau.

It is evident from this that antithetic normal faulting cannot be taken to mean that the range in which it occurs is a basin-range fault block. Antithetic normal faulting is a symptom of local lengthening, and this may occur in a basin-range fault block, in a dome or arch caused by intrusion, in the outer parts of compressional folds of the concentric type, and in any other situation involving horizontal elongation.

Compressional structures associated with intrusions of high structural relief.—Figure 8 brings out the familiar point (see, for example, Balk, 1937, p. 101-106) that intrusions of high structural relief commonly make room for themselves in part by shouldering aside the confining rocks. Most intrusive faults around the structurally steep sides of the Iron Springs intrusions are near-vertical, but some have dips as low as 45° into the intrusions. Some intrusive thrusts have throws exceeding 1000 feet (Mackin, 1954, sections C and D).

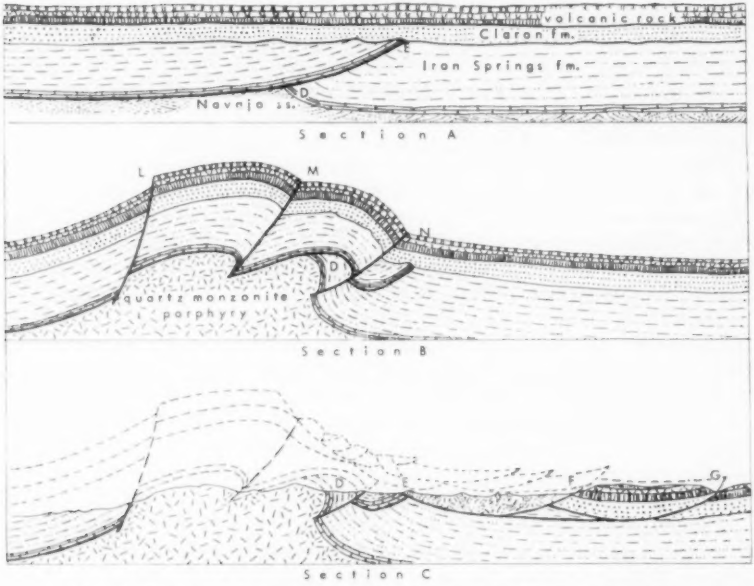

Fig. 8. Structural features associated with the Iron Mountain intrusion.

Section A. Restoration of pre-intrusive structure. A plate consisting of the Jurassic Carmel limestone and the Cretaceous Iron Springs formation moved eastward at least one mile and was beveled by erosion prior to deposition of the Eocene Claron formation and the volcanic rocks. West of D the movement was décollement over the Navajo sandstone. From D to E the thrust broke across the bedding of the Iron Springs formation (see ISGS, fig. 3).

Section B. Restoration after emplacement of the Iron Mountain intrusion, showing structures formed directly by the intrusion, but excluding the gravity slides. West of D the magma inserted itself at the horizon of the Laramide décollement zone. East of D it followed the Carmel-Navajo contact rather than the thrust where the fault plane broke across the bedding. L, M, and N are intrusive faults, normal, high angle reverse, and low angle thrust, respectively.

Section C. Same as B, but showing the gravity slides. A traverse outward from the intrusive contact near D would cross Carmel and Iron Springs autochthonous strata to the surface trace of the Laramide thrust. The allochthonous sequence east of the Laramide thrust is involved in a syncline, the east limb of which has substantially the dip imparted by Laramide deformation (compare with drawing A), while the west limb was faulted and overturned in process of emplacement of the intrusion. The axis of this syncline marks the approximate outer limit of the direct structural influence of the intrusion. Between E and F incompetent Claron and Iron Springs strata have been churned into a chaotic jumble; the stippled wedges are strike ridges of near-vertical Claron conglomerate and limestone in a matrix of Cretaceous shale and sandstone. The imbricate thrusts in the overriding volcanics are above the surface in the vicinity of this section, and the deep slide planes are far below the surface, but both of these important elements of the structure are at the surface elsewhere along the strike.

Monoclinal flexures serve the same function in the room-making process as the intrusive faults, and have the same distribution in the roofs and around the borders of the intrusions—these structures grade into each other along the strike and down the dip (Mackin, 1950, p. 65-68). The intrusive monocline

may occur as a minor structure interrupting the uniformity of the outward dip on the flank of an intrusive arch or dome, or it may stand alone as the principal border structure of an intrusive body.

Implications.—A number of workers in the basin-range province (e.g., Lasky, 1947; Nolan, 1950) have made the good point (1) that the Tertiary intrusions exposed at all levels from tops to floors make it reasonable to suppose that there must be many more not yet deroofed by erosion, and (2) that future production of metallic ores will probably come from blind ore bodies around these intrusions. The concern here is with the buried intrusions, not as "ore-bringers," but as "structure-makers."

Structures formed by intrusion can be most readily identified as such (1) where the intrusive rock is exposed, and (2) where the structures are developed in strata that are otherwise undisturbed (Baker, 1935). And it does not require much imagination to consider the possibility that the same types of structures, observed nearby in the same rocks, may have been formed by intrusions which do not crop out. This is the situation in the Iron Springs district, where four exposed intrusions, with a total area of about thirty-four square miles, have subsurface extensions or companion bodies that are at least equal to the outcropping bodies in areal extent. Throughout the district, in places many miles from the exposed intrusions, deformation structures which include thrusts and overturned monoclines in Tertiary strata are intrusive rather than tectonic.

The literature, and discussions with many geologists with diverse special fields of interest, indicate that there is a tendency to regard Tertiary intrusions in the Great Basin as stocks or plugs, rather than laccolithic bodies, unless there is compelling evidence to the contrary. This prejudice is significant for present purposes because it carriers the connotation that the area of structural influence of an intrusion is apt to be limited to the immediate vicinity of its area of exposure. When the evidence is viewed through glasses colored by use in southwestern Utah, there is reason to believe (1) that many of the Tertiary intrusions were emplaced along low-dipping planes of easy parting—bedding planes in areas of simple structure and flat thrusts in areas of complex structure, (2) that they made room for themselves largely by upflexing and upfaulting their roofs rather than assimilation or stoping, and (3) that their lateral extent and hence their areas of structural influence are in many cases very much greater than their areas of outcrop.

There is, of course, no formula for distinguishing between intrusive structures and tectonic structures. The dome, the arch, and the monocline, indeed, flexures in general as opposed to homoclines, are suggestive of intrusive origin. Intrusive faults may be normal or reverse, and they may throw away from or toward the structural high—the only common denominator of intrusive structures is that all must be parts of "enlargement" patterns, expressing the upward and outward growth of the intrusive bodies.

Dikes, sills and hydrothermal alteration effects suggest the presence of a subjacent intrusion, but the reverse is not true. These elements of the "metamorphic halo" are so remarkably limited in extent around many of the exposed Tertiary intrusions that their absence in a given structure, for example, a dome, does not mean that the structure is not intrusive.

As stated above, deformation structures formed by intrusions are most readily identified as such in strata that are otherwise flat. The difficulty of interpretation is greater (1) where the intrusive structures are superposed on one or more older generations of tectonic structures, or (2) where they have been broken and tilted by post-intrusive tectonism. Recent papers describing the deformation of flat overthrusts by exposed intrusions and further distortion of the resulting compound structures by normal faulting (e.g., Gilluly, 1956; Drewes, 1958), suggest the difficulties that may be anticipated in the diagnosis of the same types of polygenetic structures where the intrusions are concealed. A good approach to the complexities of Great Basin relationships is via Hunt's exposition of the rich variety of intrusive structures in the Colorado Plateau and his analysis of the mechanism of origin of these structures (Hunt, 1953; 1958).

It is my impression that intrusions have been greatly underrated as "structure-makers" in the Great Basin. This prejudice is helpful, not harmful—it means merely that before structural features seen in the field or described in the literature are accepted as evidence of a type of post-orogenic regional tectonism other than block faulting, due consideration should be given the possibility that they are intrusive.

STRUCTURES FORMED BY GRAVITY SLIDING FROM PRIMARY RELIEF FEATURES

The Iron Mountain slide.—Figure 8 is modeled after the Iron Mountain intrusion in the Iron Springs district. The lower drawing (section C) is a diagrammatic section through the intrusion, showing an interpretation of the present geologic relationships. The restorations in sections A and B are helpful in distinguishing three different generations of structures that are combined in section C.

Section A includes the essential elements of the pre-intrusive geology. The thrust fault is a part of the Iron Springs Gap structure (see fig. 3). It is not directly involved in the topic under consideration here, but is shown for later reference.

The second generation of structures, in Section B, belongs to the class just discussed; that is, they are structures formed directly by emplacement of the intrusion. L, M, and N are intrusive faults, normal, high angle reverse, and low angle reverse, respectively.

Section C shows a third generation of structures, formed by the sliding of huge masses of rock from the flanks of the growing intrusive dome—these structures are associated indirectly, rather than directly, with the room-making process. For what it may be worth by way of introduction to the problem, the deductive approach is as follows:

Strata known to have been substantially flat prior to the emplacement of the Iron Mountain intrusion are now near-vertical in the border zone. The structural relief of the intrusion is at least 3000 feet—the same order of magnitude as the thickness of the cover at the time of intrusion. The rate of emplacement is not known, but it is clear that there was only one episode of intrusion rather than a succession of episodes—there is no cross-cutting of solidified or partly solidified porphyry by apophyses of later porphyry. The

emplacement may have occurred during a period of a few years or a few tens or hundreds of years—the period was probably not measured in thousands or millions of years. The rate of growth of the intrusive dome as a topographic feature therefore probably greatly exceeded the rate of lowering by normal erosional processes, the more so because the uppermost of the updomed strata were massive ignimbrites of lava-like hardness. These considerations indicate that the flanks of the growing intrusive dome may well have been greatly oversteepened, and that there is nothing inherently improbable in the idea of sliding of parts of the roof on a grand scale. Burbank's analysis of stress relationships in the roofs of laccolithic domes led him to the same conclusion (1932, p. 49).

Slides from relief features produced by various types of tectonic deformation have been described in many parts of the world (for a brief analysis, see De Sitter, 1956, p. 266-292). The concept of sliding from igneous intrusive domes is less familiar, perhaps in part because only a small percentage of intrusions form topographic features steep enough to cause sliding, in part because most intrusions of pre-Tertiary age have been so deeply eroded that such slides as may have occurred have been removed, and in part because slides from intrusive domes have been interpreted as thrusts due directly to the intrusive room-making process or to regional tectonism.

To explain shallow faulting in the plains area adjacent to the Bearpaw Mountains, Montana, Reeves (1946) suggested that a load of volcanic rocks on the flanks of a low arch of probable intrusive origin was relieved plainsward by wholesale sliding along beds of bentonitic shale. Reeves' hypothesis may have to be modified because Pecora (written communication) finds that the earliest volcanic rocks of the uplift rest with angular unconformity on extensively block-faulted sedimentary formations. Evaluation of the slide hypothesis is being made by Pecora and co-workers who are currently mapping the Bearpaw Mountains uplift in detail.

Sears (1953) has recently suggested that the famous Amargosa Chaos of the Death Valley area, ascribed by Noble (1941) to Tertiary thrusting, may be in part a superficial slide associated with emplacement of an intrusion exposed nearby.

A mass of brecciated rock that clearly overlies faulted and slickensided "Tertiary lake beds," in the Contact mining district in northeastern Nevada, was regarded by Schrader as a result of a thrust fault or a landslide (1912, p. 143-145; 1935, p. 38). Schrader described the anomalous relationships competently, but he was concerned primarily with the economic geology of the district, and he did not discuss the relative merits of his two explanations. In a paper dealing with the possibility of mistaking Tertiary or Quaternary fanglomerate-mudflow breccia for evidence of Tertiary flat thrusting in the Great Basin, Hazzard and Moran favor the view that Schrader's breccia mass was formed by landsliding "related to a previous erosion cycle" (1952, p. 855). Its location about two miles south of the southern contact of a large intrusive body suggests that the sliding may have occurred at the time of emplacement of the intrusion, as at Iron Mountain, but this hypothesis does not comport with Schrader's view that the intrusion predates the "Tertiary lake beds." I have

not seen the field relations. The structure is mentioned here merely as an example of a type of anomaly—brecciated pre-Tertiary rock resting on Tertiary rock—encountered in many places in the Great Basin; the possible explanations always are (1) ordinary landslide, precipitated from a relief feature formed by erosion, (2) "gravity slide," precipitated from a relief feature formed by tectonism or intrusion, and (3) low-angle thrust.

The deductive considerations outlined above, and the other possible cases of slides from growing intrusive domes, are of interest only as background and to make it clear that the idea is not new. Field relations indicating that the crescent of complex structure southeast of Iron Mountain was formed by sliding are spelled out in detail in a report now in preparation, which includes the colored maps and sections on which a demonstration must depend. What follows is an outline of several lines of evidence intended to *explain* the slide theory, not to prove it.

Most exposures in the slide area can be mapped as consisting of one or another of eleven well-defined members of the Claron formation and the volcanic sequence. Were it not for this firm stratigraphy, which can be carried into the slide zone from the bordering areas, nothing could be done with the internal structure of the slide mass. The upper and outer part of the mass consists of a pile of imbricate plates made up chiefly of volcanic rocks in older-over-younger relationship (fig. 8, section C). The lower and inner part consists of a chaotic jumble of Claron and Iron Springs sedimentary rocks, with as many as four repetitions of the same Claron members, all nearly vertical and all with the stratigraphic tops outward. Certain individual stratigraphic units within the chaotic mass have strike lengths of as much as two miles. These "solid" slabs lie in a breccia consisting of one or several rock types. Slickensides pass from block to block through the matrix, and the breccia is so highly indurated, particularly where it is composed of volcanics, that it stands as ledges in bold relief. Clearly it is not in any sense a mudflow-fanglomerate deposit, but a crush breccia. Restoration of the structure indicates that it was formed as much as 2000 feet below the surface of the ground (fig. 8). The relationships are taken to mean that the slide consisted of two dynamically contrasted parts, an upper plate consisting of forward-riding sheets of competent volcanic rocks, and a lower chaotic mass of crushed and rotated slabs of the relatively incompetent Claron and Cretaceous sedimentary rocks.

The possibility that the structure might have been caused by Tertiary thrusting is eliminated by the fact that it occurs only adjacent to that part of the borders of the Iron Mountain and other intrusions where the intrusive contact is nearly vertical—elsewhere in the 3000 square miles that have been mapped in detail by the University of Washington group the Tertiary sedimentary and volcanic rocks show no suggestion of this type of structure, or other evidence of strong regional compression. Moreover, the pattern of the deformation, both with regard to gross distribution and the orientation of internal structures, proves that the movement was not in any one compass direction but was radially outward from Iron Mountain to the south, southeast, and east.

The possibility that the structure could have been formed directly by the intrusion, as part of the room-making process, is eliminated because it starts half a mile to a mile out from the intrusive contact, on the far side of a normal intrusive border zone (fig. 8) and by other relationships that can be shown adequately only on detailed maps and sections.

Slides from tectonic features.—Some Great Basin fault scarps stand at angles considerably exceeding the angle of repose, and it is likely that block faulting was more active at some places and times during the Tertiary than it is now. There is, therefore, nothing inherently improbable in the proposition that slides, of the same order of magnitude as those on the east side of Iron Mountain, may have been shed from oversteepened fault scarps. The possibility that the "turtle-back complexes" of Death Valley were formed in part by sliding was not eliminated by evidence outlined in Curry's preliminary statement (1954) of his theory that the "turtlebacks" are folded parts of flat thrusts of Tertiary age. No attempt to evaluate sliding (Bucher, 1956, p. 1310-1311) versus Tertiary thrusting as an explanation of the features of the Death Valley area is needed here. It may be stated simply that sliding is a possible or even likely alternative to Tertiary thrusting in the Great Basin as an explanation of structural complexities involving Tertiary rocks, particularly if these complexities are localized near major structural features, whether intrusive or tectonic. The slide concept is easy to grasp where the structural anomalies are in the shadow of a high range; it is not so obvious, but no less likely, where erosional reversal of topography has reduced to a lowland the elevated place from which the slides might have been shed.

Earl Cook suggested in the field that erosion remnants of slides should be called, not klippen, but slippen. This term certainly does not belong in our new glossary, but it is a good catchword, well suited to keep in mind an hypothesis that is an essential part of the mental field equipment of geologists working in the Great Basin.

POST-OROGENIC VS OROGENIC STRUCTURES

Introduction.—To this point the focus has been on ignimbrites as reference planes for measurement of post-Laramide deformation; Laramide orogenic structures have been considered simply as elements of a pre-Tertiary "basement complex." Here the emphasis shifts to use of the ignimbrites in distinguishing between the effects of orogenic and post-orogenic deformation. There are two points of view:

To the geologist concerned primarily with the orogenic deformation, the structure of the Tertiary volcanics may be of interest only as a measure of a distortion that must be removed from the structures of the subjacent rocks as a first step in analysis of these older structures. The student of Tertiary deformation is concerned with the opposite side of the same coin; if he mistakenly considers certain structures, actually formed during the Laramide orogeny, to be post-orogenic, this error is certain to vitiate his analysis of post-orogenic deformation.

The discussion to follow proceeds from the simple case of removing the distorting effects of block tilting from orogenic structures, to the somewhat

more complicated case in which a major basin-range fault corresponds in position with an overturned Laramide fold, and to the complexities caused by superposition of Tertiary intrusive structures on a Laramide thrust.

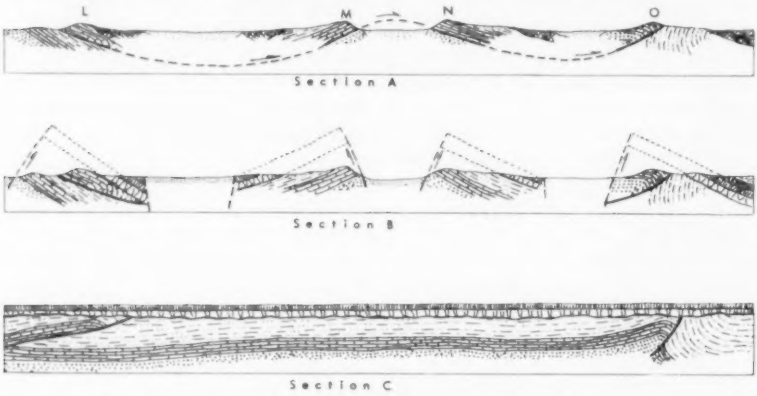

Fig. 9. Distortion of an orogenic structure by Tertiary deformation.

Sections A and B show contrasted interpretations of two different issues: (1) whether there is or is not a single thrust of regional extent: and (2) whether deformation after the main orogeny was by folding or block faulting. These issues are entirely independent of each other; the regional thrust might as well have been combined with post-orogenic block faulting in Section B as with late- or post-orogenic folding in Section A.

Section C is a restoration prior to the beginning of Tertiary deformation, based on the attitudes of the older rocks after the volcanics are rotated back to the horizontal.

Effects of simple rotation.—Section A in figure 9 shows three sedimentary rock units, a sandstone, a limestone, and a shale, exposed in four ranges, L, M, N, and O, separated by volcanic rock and alluvium. In ranges L and O low angle thrusts bring the limestone over the younger shale. In ranges M and N the sedimentary rocks are in the normal order of superposition, but there is a zone of gliding at the contact of the sandstone and the limestone.

The heavy dashed line in Section A shows an interpretation of the structure based on the attitudes of faults and bedding in the pre-Tertiary rocks only, that is, on the basis of geologic observations in the Spurr tradition which lumps the Tertiary volcanic rock with the alluvium as part of a superficial blanket, and leaves the landforms to the physiographers. According to this interpretation, the older-over-younger thrusts in ranges L and O, and the planes of younger-over-older décollement gliding in ranges M and N, are at the base of the same far-traveled thrust plate. Folding of the thrust may be assigned to a waning stage of the orogeny or, if the attitudes of the volcanics are taken into account, the folding may be considered to be Tertiary. If the implication that the flat-floored basin between ranges M and N was developed by erosion in resistant sandstone is disturbing, minor range-front faults can be postulated, but these are incidental to the bed rock structure.

Figure 9 B is an alternative interpretation of the same observational data, but with the attitudes of the volcanics credited to block faulting.

Figure 9 C is a restoration of the Laramide structure, drawn to conform with the attitudes in the older rocks corrected by rotating the volcanics back to horizontality. The thrust in range L was formed with a westerly dip of 15°, not an easterly dip of 17°. The thrust in range O is an entirely different structure; the original dip was 65°. The amount of décollement movement in ranges M and N is not known but may be only a few tens of feet or hundreds of feet. Bedding-plane gliding is to be expected at contacts of rock units of different competence even in areas of mild deformation; the zones of gliding in ranges M and N are not evidence that the thrust faults in ranges L and O are parts of a single flat thrust of regional dimensions.

The restored section of figure 9 C is modeled after relationships in the Great Basin-Colorado Plateau transition zone in southwestern Utah. The western of the two structures is the Iron Springs Gap thrust seen on the east side of the Iron Mountain intrusion (fig. 8). The eastern structure is the Kanarra fold of Gregory and Williams (1947). The unconformable cover, shown in the sections as consisting entirely of volcanics, actually is made up of the Eocene Claron formation overlain concordantly by the volcanics (compare with fig. 3).

The Iron Springs Gap thrust and the Kanarra fold are about 15 miles apart. The Claron is substantially conformable with the Cretaceous between these structures, and east and west of them. The Iron Springs Gap thrust is clearly a foreland structure, similar in all essential respects to the Pine Mountain thrust of the Cumberland Plateau (Rich, 1934; King, 1951, p. 128-130). The counterpart of the Chattanooga shale as a widespread zone of décollement gliding in the southeastern Great Basin is a zone of shaly and gypsiferous limestone near the base of the Carmel limestone, just above the top of the Navajo sandstone. The Kanarra fold cannot be considered a "break through" from this décollement horizon because the fold involves the Navajo and subjacent rocks at least as old as Kaibab. It exhibits the strongly compressional features of the Iron Springs Gap thrust but in other respects is more closely akin to the east-throwing Laramide monoclines of the Colorado Plateau. The relationships shown in figure 9 C are not easily seen in the field or on a geologic map because both the Laramide structures are obscured, not only by simple block tilting of the type shown in figure 9, but also by strong and sharply localized Tertiary deformation (Threet, paper in preparation).

A basin-range fault superposed on an orogenic structure.—The Kanarra fold, overturned and overthrust to the east, was beveled by erosion and the stump was covered by the Eocene Claron formation and silicic volcanic rocks of probable Oligocene age prior to the beginning of Hurricane faulting (fig. 10A). Hurricane faulting began in mid-Tertiary time and has continued to the present (fig. 10B). Two surficial elements which further complicate the field relations but have been omitted from the diagrammatic sections are: massive rock slumps of the Toreva type (Reiche, 1937), which clutter parts of the fault scarp; and basalt flows of several ages, broken and tilted by jogs of movement in the fault zone (Gardner, 1941).

In a segment of the Hurricane scarp south of Cedar City, Utah, the Claron formation and the silicic volcanics have been entirely removed by erosion except for remnants at the base, as shown in figure 10B. Rocks of Permian to

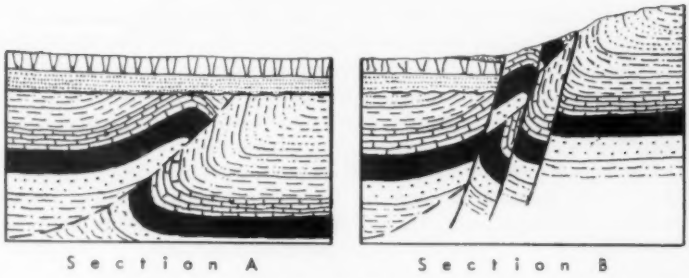

Fig. 10. Structure of the Hurricane fault zone.

The rock units shown diagramatically in the Kanarra fold in Section A do not correspond with the actual stratigraphic succession, which ranges in age from Permian to Cretaceous. The unconformable cover consists of the Claron formation overlain by volcanic rocks.

As indicated in Section B, the Claron and the volcanics have been entirely removed by erosion from the upthrown side of the Tertiary Hurricane fault. The compressional structures that characterize the fault zone long predate the movement that formed the scarp.

Cretaceous age composing the fault zone are in many places vertical or overturned, and are involved in eastward thrusts. The scarp is clearly due to late Tertiary and Quaternary faulting. These relationships might well be taken to mean that the compressional structures in the fault zone were formed by the crustal movement that made the scarp; that is, that the Hurricane fault is a complexly shattered thrust of late Cenozoic age. That the compressional structures predate the beginning of movement on the Hurricane fault, and that the history is that shown in the diagrams, must be pieced together: (1) from the work of Cook to the south, where a part of the west limb of the Kanarra fold is capped by Claron and volcanic rocks on the down-thrown side of the Hurricane fault (Cook, 1957, fig. 46); (2) from the work of Threet to the north (1952, pl. 3), where the east limb of the fold is similarly capped on the upthrown side of the fault; and (3) by analogy with the Iron Springs Gap structure, which is preserved in its entirety, with its unconformable cover of Claron and volcanics, in the Iron Springs district (Mackin, 1954).

Similar cases of alignment of basin-range faults, which control the present topography, with older compressional structures have been described along the eastern border of the Great Basin in central Utah by Eardley (1933, 1951, p. 325-336) and Spieker (1949).

Distortion of an orogenic structure by a Tertiary intrusion.—Figure 8 shows clearly the theory that the Iron Springs Gap structure, a low-angle thrust of Laramide age, was turned on end by emplacement of the Iron Mountain intrusion. The evidence on which this view is based will be presented elsewhere—the structural relationships would be equally effective for present purposes if they were entirely hypothetical. It is evident (1) that analysis of the Laramide structure must start with subtraction from it of the deformational effects of the intrusion, and (2) that this operation is dependent on the presence of the Claron in the role of a reference plane known to have been flat after the orogeny and prior to the intrusion.

It might seem that the best way to learn the form of the Laramide structure would be to map it in places where there is no intrusive distortion. The difficulty is that there are no such places. At least six intrusions of the Iron Mountain type are aligned along the structure in southwestern Utah, and it is exposed only where the intrusive uparching has caused removal of the Tertiary cover.

The Claron and the volcanics make it possible not only to separate the deformational effects of the orogeny from those of the intrusion, but also to establish their relative ages. The six intrusions mentioned above are evidently localized along the orogenic structure, but this does not mean that they were formed during the orogeny, as might appear likely on deductive grounds. Emplacement of the intrusions is definitely post-orogenic; the interval was long enough for beveling of the Iron Springs Gap thrust, deposition of the nonvolcanic "red Claron" and the tuffaceous "gray Claron," and spreading of two sequences of ignimbrites.

The complexity resulting from superposition of intrusive structures on older orogenic structures is such that the two generations of structures are apt to be confused, particularly if conclusions are based on study of an area too small in size to provide an adequate variety of structural and stratigraphic relationships. For example, the Iron Springs Gap thrust, which can be readily proven to be a regional tectonic structure, might easily be connected underground or through the air in figure 8C with the slide plane which passes beneath the chaotic structure in Tertiary rock in the outer part of the intrusive border zone. This type of error results in a misreading of both the orogenic and post-orogenic history. In this instance both the Laramide thrust and the Tertiary slide are lost to the record, and their unhappy combination is a Tertiary thrust which is not there.

GENERAL SUMMARY

Gilbert and his colleagues concluded, primarily on physiographic grounds, that the ranges of the Great Basin were formed by a type of deformation—"dominantly vertical displacements of comparatively rigid blocks"—markedly different from the deformation recorded by the tight folds, low angle thrusts, and other orogenic structures exhibited by the pre-Tertiary rocks composing the ranges. Many later students of the Great Basin have been led by physiographic and other lines of evidence to the same fundamental generalization: that the block fault type of tectonism represents not merely the waning of the orogeny, but a distinctly different phase of the diastrophic cycle, with habits of deformation different in kind from those of the orogenic phase.

Within this generalization there are many questions: Was the block faulting episodic in a regional sense, with brief periods of province-wide faulting separated by protracted periods of crustal quiet? Or was it in some other manner systematic, as spreading in one or more waves entirely across the Great Basin from one side to the other, or outward from the center toward both sides? Or was it seemingly haphazardly distributed in space and time? Was there a period of quiesence between the close of the orogeny and the beginning of the block faulting? Or was the deformation continuous, merely

changing in type, abruptly or gradually, and everywhere at the same time or at different times in different places? Equally critical to any analysis of the post-orogenic deformation is a knowledge of the geometry of the fault blocks, including their sizes, the dip of the faults relative to the direction of tilting, and especially whether the tilt directions are haphazard or are systematically oriented in different parts of the province.

The principal point made in this paper is that ignimbrites, formed by nuées ardentes of incredible magnitude which swept with hurricane velocity across much of the Great Basin again and again during the post-orogenic period, provide a basis for cross-dating the block faulting and other geologic events with the precision required if the questions as to relative timing outlined above are to be answered. Because they were originally flat-surfaced, the ignimbrites permit exact and detailed measurement of the post-orogenic crustal movements. And they are unique stratigraphic units in still another sense—most of them contain enough radioactive material to permit determination of "absolute" age within certain limits of error, which will surely be reduced as the methods are perfected.

It might be argued that, because there has been strongly compressive deformation during the Tertiary in California, there *should* have been folding and thrusting at the same time in the Great Basin. This sort of deductive reasoning, whether based on observed relationships in an adjoining province or on general concepts as to stress conditions in or under the crust, is all right in its way. But it has been demonstrated in district after district, by physiographic evidence and by mapping of the Tertiary volcanics, that the Gilbert theory of the block fault origin of the Basin ranges is valid, and that the range front faults are as a rule normal. This does not by any means eliminate the possibility that there were episodes of strongly compressive regional tectonism in the Great Basin in the Tertiary. It may be even true that all of the post-orogenic deformation has been compressive in some places. Perhaps some of the ranges *are* doubly-plunging Pliocene anticlines. The point made here is that, in a province where the characteristic type of Tertiary deformation has been a jostling of blocks bounded by normal faults, evidences of strongly compressive regional tectonism are of special interest and importance to our eventual understanding of causes and mechanisms of the post-orogenic movements, and should be fully reported. An obvious requirement of such reports is a statement of the evidence indicating that the compressional structures *are* post-orogenic, and that they were not formed by emplacement of hypabyssal intrusions, nor by gravity sliding from relief features raised by intrusion or high angle faulting.

The Tertiary ignimbrites have been considered here primarily as rock layers of great areal extent which permit the working out of the post-orogenic deformational history in a degree of accuracy and detail that would not otherwise be possible; the "structural significance of the volcanic rocks" in this article is entirely descriptive. An article to follow shortly will develop the hypothesis that the eruptive activity and the deformation are related also in a genetic sense, that is, that episodes of block faulting which have occurred from time to time and from place to place during the Tertiary represent failures of

the crust due to withdrawal of lateral support caused by frothing eruption of many thousands of cubic miles of magma formed by fusion of crustal rock.

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STUDIES IN THE SYSTEM CaO–Al_2O_3–SiO_2–H_2O, II: THE SYSTEM $CaSiO_3$–H_2O*

DEAN A. BUCKNER[1], DELLA M. ROY and RUSTUM ROY

Department of Geophysics and Geochemistry, Pennsylvania State University, University Park

ABSTRACT. Phase equilibria in the system $CaSiO_3$—H_2O were studied, and a p-T curve constructed for the upper stability of xonotlite. The maximum stability of xonotlite is about 420°C at 20,000 psi for $CaSiO_3$. 1/5 H_2O, but is raised to about 500°C by the substitution of 7.5 wt. percent $SrSiO_3$. At higher contents of $SrSiO_3$ a new anhydrous phase appears, herein called μ-$(Ca,Sr)SiO_3$. Well-crystallized 11 Å tobermorite, having the composition $4CaO \cdot 5SiO_2 \cdot 5H_2O$ is stable up to about 285°C at 15-30,000 psi, where it decomposes to xonotlite (+ truscottite? + H_2O). The crystallization of scawtite and its relation to the tobermorite decomposition is discussed. New data on the phases are presented and the petrological and crystallo-chemical significance discussed.

INTRODUCTION

Phase equilibrium studies have proven to be of great value in the elucidation of petrologic and crystallochemical problems. A study of the system $CaSiO_3$—H_2O was undertaken to determine the stabilities of xonotlite and lower-temperature calcium silicate hydrates as a function of temperature and pressure, and their relationship to the formation of wollastonite. The effect of Sr^{2+} in solid solution on the stabilities of the phases is furthermore of general crystallochemical interest because of the similarity of Sr^{2+} to Ca^{2+}. The data obtained might then be related to certain specific problems, such as defining the interrelation of xonotlite and wollastonite in contact deposits, and limiting the conditions of petrogenesis in these areas. Data on the tobermorite decomposition, as well as defining stability ranges in natural deposits would contribute knowledge applicable to the study of portland and high temperature cement hydration mechanisms.

The work on calcium silicate hydrates in general is too extensive to review in detail here; however, the hydrothermal studies of Flint, McMurdie and Wells (1938) and Taylor and Heller (1951) are relevant. The recent books of Bogue (1955) and Heller and Taylor (1956) contain excellent reviews of the conditions of formation and properties of calcium silicate hydrates, including those in the system $CaSiO_3$—H_2O. The present-study was carried out mainly in 1954-1955, and a reexamination of the tobermorite stability was carried out in 1958.

EXPERIMENTAL

Starting materials.—A variety of starting materials was tried during the course of this investigation. Those giving the best reactions were:

1. Glasses prepared from $CaCO_3$, $SrCO_3$, and H_2SiO_3.

2. Gels prepared from $Na_2SiO_3 \cdot 9H_2O$ and $Ca(NO_3)_2 \cdot 4H_2O$ (precipitated together and washed with excess $Ca(OH)_2$): and from coprecipitation of

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[1] Present Address, Bausch and Lomb Research Laboratories, Rochester, N. Y.

$Ca(NO_3)_2 \cdot 4H_2O$ and ethylorthosilicate. These gels will be referred to as Gels I and II respectively.

3. Synthetic xonotlite prepared by reacting a mixture of $Ca(OH)_2$ and H_2SiO_3 at 350°C and 5,000 psi water pressure for three weeks.

4. Quite pure natural xonotlite.[2]

5. A mixture of $Ca(OH)_2$ and H_2SiO_3 ground under alcohol.

Methods and equipment.—Treatment of the samples was carried out using established hydrothermal techniques (Roy and Osborn, 1952; Roy and Tuttle, 1956). In addition to the stainless steel and stellite test-tube type bombs used for hydrothermal runs, a one-liter autoclave was used in the production of a fifty gram batch of xonotlite. Glass melts were made in a gas furnace and for higher temperatures on a platinum strip furnace. Infra-red spectra were obtained on a Perkin-Elmer Model 21 double-beam spectrometer, with an NaCl prism.

Identification of the phases.—Phases were identified by powder x-ray diffraction, using a Norelco wide-range diffractometer, and by the polarizing microscope. X-ray diffraction was used for routine identification because of the very small particle size.

RESULTS

The upper stability of xonotlite

The stability range of xonotlite was studied hydrothermally. More than 230 runs were made ranging in duration to 312 hours and utilizing pressures up to about 2,000 atmospheres (see table 1). Most data were obtained from samples treated at 5,000 and 20,000 psi. A p-T curve for the reaction xonotlite $\rightleftarrows$ β-$CaSiO_3$ + H_2O is shown in figure 1.[3] The data show that at 20,000 psi xonotlite is stable to 418±10°C, and at 5,000 psi the limit is 400±10°C. The parameters were also checked at 10,000 and 28,000 psi. Below 5,000 psi reaction was too slow to obtain reliable data from reactions made over such relatively short times.

Starting materials found to be best for this study were; glass, xonotlite and the gel mixtures. Starting materials other than xonotlite metastably convert partly to β-$CaSiO_3$ between about 350°C and the upper limit of the xonotlite stability. β-$CaSiO_3$, once formed is very difficult to re-hydrate to xonotlite.

Data on the stabilities of the lower temperature hydrates of calcium metasilicate

General.—Hydrothermal reactions at low temperatures are notably slow in this system, and this slow rate of reaction makes difficult the interpretation of phase equilibrium data. Since this work was first done (Buckner and Roy, 1955) some more recent studies on tobermorite have pointed out further avenues for work. At least three, perhaps four, states of hydration of tobermorite are known to exist (see Heller and Taylor, 1956 and Taylor and Howison, 1957 for a review), having basal spacings of approximately 14 Å.

[2] The authors are indebted to Professor Murdoch of U.C.L.A. and Dr. George Switzer of the Smithsonian Institute for providing samples of xonotlite.

[3] Since powder x-ray data do not easily distinguish wollastonite from para-wollastonite, β-$CaSiO_3$ is used, following the practice of Dent and Taylor (1956), to represent the low-temperature in contrast to the high-temperature modification pseudo-wollastonite.

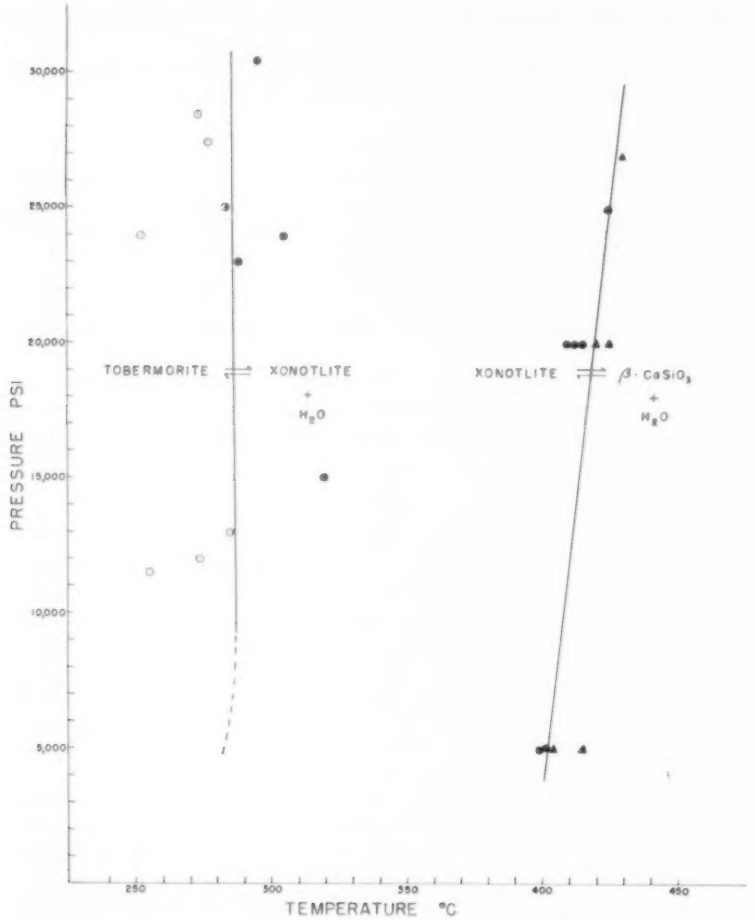

Fig. 1. Univariant p-t curves for the reactions tobermorite = xonotlite + H_2O (or = xonotlite + truscottite + H_2O) and xonotlite = β-$CaSiO_3$ + H_2O determined from data in tables 1 and 2. Open circles = tobermorite, solid dots = xonotlite, triangles = β-$CaSiO_3$.

11 Å, 9 Å, and perhaps 10 Å. The 11 Å hydrate is considered to be the most stable and best crystallized, and the structural determinations by McConnell (1954) and Megaw and Kelsey (1956) were on the natural mineral having the composition $5CaO{\cdot}6SiO_2{\cdot}5H_2O$. Kalousek and Roy (1957) and Kalousek and Prebus (1958) found that the best crystallized material (11 Å) was formed from compositions higher in silica than 1:1 $CaO{:}SiO_2$, ($4CaO{\cdot}5SiO_2{\cdot}5H_2O$ being the best) and was formed readily from $Ca(OH)_2$—quartz mixtures;

TABLE 1

Reaction: xonotlite ⟷ β-$CaSiO_3$ + water

Run No.	Temp. (°C)	Pressure (psi)	Time (hrs)	Initial Condition	Result
	Composition $CaSiO_3$*				
655	430	27,000	282	Glass	β
569	425	25,000	52	"	Xon + β
623	430	20,000	67	"	β
689	425	"	181	"	β
282	420 ± 4	"	130	"	β
641	416 ± 5	"	312	"	β + little Xon
314	412 ± 8	"	113	"	β + little Xon
401	412	"	72	"	β + Xon
271	411 ± 3	"	65	"	β + Xon
427	366	"	132	"	Xon + β
444	352	"	64	"	Xon + β
606	480	10,000	190	"	β
578	350	"	192	"	Xon
174	423	5000	73	"	β
195	404	"	240	"	β
257	402	"	77	"	Xon + β
248	396	"	89	"	Xon + β
656	430	27,000	282	Xon	Xon + β
567	425	25,000	52	" (Calif)**	Xon
642	416 ± 5	20,000	312	" "	Xon + little β
588	399 ± 20	"	246	" "	Xon
657	430	27,000	282	Xon	β
643	416 ± 5	20,000	312	" (Auto)***	β + little Xon
590	399 ± 20	"	246	" "	Xon
263	445	20,000	69	Gel-I	β
315	412 ± 8	"	113	"	β + little Xon
403	410	"	72	"	β + Xon
414	390	"	72	"	Xon + v.l. β
230	415	5000	48	"	β
258	402	"	77	"	Xon + β
243	399 ± 7	"	124	"	Xon + little β
264	445	20,000	69	Gel-II	β + v.l. Xon
316	412 ± 8	"	113	"	β + v.l. Xon
404	410	"	72	"	β + Xon
415	390	"	72	"	Xon + v.l. β
259	402	5000	77	"	Xon + β
244	399 ± 7	"	124	"	Xon + little β
638	406	20,000	168	β	β + v.l. Xon
410	350 ± 20	"	162	β	β + v.l. Xon
610	460	"	233	α	β + little α
639	406	"	168	α	β

TABLE 1 (Continued)

Reaction: xonotlite $\longleftrightarrow$ β-$CaSiO_3$ + water

Run No.	Temp. (°C)	Pressure (psi)	Time (hrs)	Initial Condition	Result
		Composition C2-1/2 S			
693	516	20,000	181	Glass	β
690	425	"	181	No. 664	β + v.l. Xon
664	375	"	303	Glass	β + Xon
352	508	5000	46	"	β + Xon
209	480	"	19	"	β
169	476	"	41	"	β
179	455	"	48	"	β + Xon
222	429	"	57	"	Xon + β
188	425	"	96	"	β + Xon
311	413	"	114	"	Xon + β
359	513	5000	114	Xon	β + v.l. Xon
357	471	"	114	"	β + v.l. Xon
		Composition C7-1/2 S			
532	533	20,000	46	Glass	β
694	516	"	181	"	β
25	548	9,000	71	"	β
353	508	5,000	46	"	β + Xon
307	491 ± 20	"	41	"	β + some Xon
157	476	"	92	"	β
343	474	"	87	"	β + Xon
319	454	"	121	"	β + Xon
189	425	"	96	"	β + Xon
		Composition C 25 S			
151	178	5,000	70	Glass	Xon
109	355	2,500	24	"	μ
636	434	500	68	"	Xon + β
648	267	500	120	"	Xon
		Composition C 50 S			
58	362	10,000	42	Glass	Xon + α
637	434	500	68	"	α + little Xon
649	267	500	120	"	Xon + α

* Compositions given as wt. % ratios; i.e., C 2-1/2 S = $CaSiO_3$ 97.5%, $SrSiO_3$ 2.5% (by weight).

** Xon (Calif) = Natural Xonotlite from Riverside, California.

*** Xon (Auto) = Xonotlite Prepared in the Autoclave.

whereas the 14 Å hydrate was more poorly crystallized, and was formed from $Ca(OH)_2$—silicic acid mixtures of the 1:1 CaO:SiO_2 ratio.

Data on tobermorite decomposition.—In the earlier part of the present study, an attempt was made to study the equilibrium decomposition of tober-

morite to xonotlite, with the result that an intermediate phase "B" was formed throughout a temperature interval of about 50°C. This phase resembles the "extra lines B" of Taylor and Heller (1951), first reported by Flint, McMurdie and Wells (1938) as a calcium monosilicate hydrate, more recently called CSH(A) by Bogue (1955), but which also bears a very strong resemblance to scawtite. Those runs which show this intermediate phase are given in part 2 of table 2.

More recent runs were made with various types of gels and mixtures, as well as with two samples of synthetic tobermorite.[4] Most gels readily pick up CO_2 on exposure to air, so the best data are considered to be those from decomposition of well-crystallized tobermorite. However, it is desirable to have a check on the maximum temperature of formation, as well as of decomposition —hence some results from one of the mixtures are reported as well. Another mixture, using $Ca(OH)_2$ + amorphous silica ("Cabosil") always formed gyrolite or truscottite[5] first, and only very slowly yielded tobermorite.

The results of the runs are summarized in table 2, part 2. Tobermorite as extracted from the hydrothermal apparatus and examined under ambient conditions was always present as the 11 Å hydrate. Preformed tobermorite converted directly to xonotlite, not via a 9 Å intermediate phase. From the data obtained the temperature for the reaction, tobermorite = xonotlite + H_2O (or tobermorite = xonotlite + truscottite + H_2O) is placed at about 285°C in the pressure range studied. Little difference was observed between the results at pressures ranging from about 12,000 to 25,000 psi, as is shown in figure 1.

Some explanation of the interpretation of these data is necessary. It is considered that the runs made in sealed tubes provide the most valuable information, since they prevent the entrance of CO_2 during the course of the run. However, reaction is slow at best, and extremely slow under the confinement of the tubes. Even after long runs, or runs considerably above the decomposition temperature (e.g. at 340°C) only partial conversion to xonotlite was usually obtained. Therefore, the presence of a small amount of xonotlite was considered indicative of the xonotlite stability field. Furthermore, the maximum temperature of formation and persistence of tobermorite from the mixture CS-44 (though contaminated by admixture of unreacted quartz, and $CaCO_3$) was almost the same. Little difference in decomposition temperature was observed between the 4:5:5 and 5:5:5 tobermorites; however, there is some evidence that the latter may decompose at a slightly lower temperature and react somewhat more quickly to form xonotlite, or if CO_2 is present, scawtite. The presence of truscottite as a second phase from decomposition of 4:5:5 was observed, which is reasonable from the standpoint of composition; however, data are insufficient as yet to establish a stability region for truscottite. At lower temperatures gyrolite was often observed as an early product from the reaction of gels.

[4] This tobermorite was the same as that used in the study by Kalousek and Roy (1957).

[5] Recently, Strunz and Micheelsen (1958) have shown that reyerite is identical with truscottite and the former name has precedence.

TABLE 2 (part 1)

Data on Low-Temperature Hydrates

Temp. (°C)	Pressure (psi)	Time (da)	Remarks	Product
		Tob 4:5:5 $CaO:SiO_2:H_2O$ 11 Å		
175	15,000	2		Tob**
187	15,200	20		Tob
203	25,000	5		Tob
255	11,500	7		Tob
252	24,000	20		Tob
274	12,000	4		Tob
285	13,000	22	S*	Tob
288	23,000	13		Tob + l Sc + l Xon
295	30,500	20	S	Trus + gyr + tob + Xon
305	24,000	17		Tob + Cc + Xon
320	15,000	11	S	Tob + l Xon
340	15,500	2	S	Tob + l Xon
		Tob 5:5:5 $CaO:SiO_2:H_2O$ 14 Å		
203	25,000	5		Tob
240	16,000	14		Tob
262	14,200	3		Tob
273	28,500	29	S	Tob
285	13,000	22	S	Tob
288	23,000	13		Tob + l Cc
295	30,500	20	S	Xon
305	24,000	17		Cc largely
		CS-44 $5Ca(OH)_2 + 6SiO_2$ (quartz) mix		
160	21,000	13		Tob + l Q + l Cc
187	15,200	20		Tob + l Cc + l Qtz
244	16,000	6		Tob + l Cc + l Qtz
255	11,500	7		Sc + Tob + Cc + Qtz
273	28,500	29		Sc + Tob + Cc + Qtz
274	12,000	4		Sc + Qtz + Cc + Tob
277	27,500	11		Tob + Qtz + Sc + Cc
285	13,000	22		Tob + Qtz + Cc
283	25,000	5		Tob + Qtz + Cc + l Xon
288	23,000	13		Sc + Qtz + l Cc
295	30,500	20	S	Cc + Qtz + Xon
305	24,000	17		Cc + Qtz + Sc
320	15,000	11	S	Cc + Sc + Qtz + Xon

* S = run in sealed Au tube; others are not sealed.

** Abbreviations used: Tob = tobermorite, the 11 Å basal spacing unless otherwise indicated; l = little, Sc = Scawtite, Xon = xonotlite, Qtz = quartz, Cc = Calcite, Trus = Truscottite, Gyr = gyrolite, β = β-wollastonite, v.s. = very strong, "B" = probably scawtite—(possibly $CaO \cdot SiO_2 \cdot H_2O$ or CSH (A) in Bogue's terminology).

*** Mix = Mixture of $Ca(OH)_2 + H_2SiO_3$.

The presence of scawtite, "B" or CSH(A)

Although in the earlier part of the study the phase "B" was obtained quite reproducibly, later evidence suggests that it is not a true equilibrium phase in the system $CaO—SiO_2—H_2O$. Scawtite having a powder x-ray diffraction pattern in very good agreement with those reported by Murdoch (1955) and McConnell (1955) was formed especially under those conditions where CO_2 is inevitably present. The possibility that "B" was related to 9 Å

TABLE 2 (part 2)

Temp. (°C)	Pressure (psi)	Time (hrs)	Initial Condition	Result
			Composition $CaSiO_3$	
360	28,000	144	Glass	Xon + β
352	20,000	64	"	Xon + β
279	5,000	19	"	Xon
272	"	92	"	Xon
200	"	19	"	Xon + "B"
198	"	52	"	Xon + "B"
178	"	70	"	Tob + "B"
250	20,000	162	Xon	Xon + "B" v.s.
230	"	162	" (Auto)	Xon + "B" weak
150	"	162	" "	Xon
208	15,000	164	"	Xon
250	20,000	162	Mix***	Tob + "B"
230	"	162	"	Xon + "B"
150	"	162	"	Tob + Xon + "B"
208	15,000	164	"	Tob + "B"
162	"	93	"	Tob
			Composition 95$CaSiO_3$, 5$SrSiO_3$ (weight) or C5S	
142	5,000	144	Xon	Xon + 1 Tob?
174	"	170	"	Xon + 1 Tob?

tobermorite was considered earlier; however, failure in the more recent runs to obtain any 9 Å tobermorite spacing reproducibly in connection with the "scawtite" pattern would appear to eliminate this possibility. Truscottite has a strong 9.4 Å reflection, but other spacings clearly distinguish it from a possible 9.3 Å tobermorite.

The recent paper of Murdoch and McConnell (1958) may be relevant in explaining a mechanism for the growth of "scawtite" from almost-pure $CaSiO_3$—H_2O mixtures. To explain variations in CO_2 and SiO_2 content of different scawtite specimens they postulated an isomorphous substitution of $(4CO_3^{2-})$ and $(3SiO_4^{4-})$, which would vary inversely. In the event of extensive substitution of SiO_4^{4-} for CO_3^{2-} in the scawtite structure, the composition may approach that for CSH(A), which might then exist stably over a very small temperature interval between the decomposition of tobermorite and the formation of xonotlite. More complete structural and compositional data will be necessary to determine positive limits of substitution of SiO_4^{4-} for CO_3^{2-} in the scawtite structure, but the bulk of evidence points to an essential identity of scawtite, CSH(A) and the phase "B". Certainly under most conditions of formation in natural deposits and industrial cement processes sufficient CO_2 would be present to form scawtite.

Effect of Sr on the hydrated phases

Not much information has been obtained on the effect of strontium solid solution on the hydrated phases. This is partly due to the interference of a new phase, herein called (μ–(Ca,Sr) SiO_3) and partly due to the lack of a good starting material. The only starting material used in the study of the effect of Sr^{2+} solid solution was glass.

The best data obtained from hydrothermal treatment of the various Sr^{2+} containing glasses indicate that the presence of the Sr^{2+} ion stabilizes xonotlite to a higher temperature than the pure calcium xonotlite (see table 1). It may be thus stabilized to about 500°C at 7½ wt. percent $SrSiO_3$. At higher contents of $SrSiO_3$ the new phase appears (see fig. 3 and tables 1 and 4).

There is no evidence that either scawtite (including CSH(A) and the "B" phase) or tobermorite was formed from these Sr-containing compositions, although they are represented in figure 3. This absence of tobermorite-like phases is thought to be the result of the starting material (glass) which resulted in formation of xonotlite far below its lower stability limit even from pure $CaSiO_3$.

New data on xonotlite

D.T.A.—D.T.A. curves were obtained from natural xonotlite, which shows no thermal effects until a rather sharp endothermic reaction at about 840°C. A portion of the sample removed at 864°C and x-rayed showed that the xonotlite had completely decomposed to β-$CaSiO_3$. The same endothermic effect was observed with the synthetic xonotlite, however, the effect was much less sharp and the peak temperature was somewhat higher. It is noteworthy therefore that no "amorphous" or "meta-xonotlite" stage is encountered. The direct formation of β-$CaSiO_3$ also indicates that there is no marked predisposition to any other structure.[6]

Dehydration studies.—Natural xonotlite was dried at 110°C for several hours, heated at 680°C for four hours then at 880°C for one hour. Weights were recorded after the drying and each heating step. The results are tabulated in table 3. Tabulated also are the data for the weight loss of synthetic xonotlite, which was dried for twenty-four hours at 110°C, heated over night at 286°C, then at 650°C for three hours, again at 650°C overnight and, finally, at 880°C for four hours.

TABLE 3

Data on the Weight Loss of Natural and Synthetic Xonotlite

Natural Xonotlite

°C	% Loss	n*	$CaSiO_{3/H_2O}$
110-880	3.14	.209	4.78
680-880	2.54	.168	5.95

Synthetic Xonotlite

°C	% Loss	n*	$CaSiO_{3/H_2O}$
110-880	3.575	.239	4.2
650-880	2.34	.155	6.45

* n refers to the number of moles in the formula $(CaSiO_3 \cdot nH_2O)$

The several heating steps below the decomposition of xonotlite revealed a continuous loss of water with time. Therefore, the data on weight loss between

[6] This result has been confirmed by Dent and Taylor (1956) in single-crystal x-ray studies of the xonotlite $\rightleftarrows$ wollastonite transformation at atmospheric pressure.

100°C and 880°C probably represent a loss of the adsorbed water as well as some "structural" water. X-ray patterns of the samples heated at 650°C show no difference from those of the original samples. X-ray patterns of the samples after being heated at 880°C show only the β-$CaSiO_3$ phase. Therefore, the data on weight loss between 650°C and 880°C are considered to be the most significant. Inasmuch as the xonotlite samples show a continuous water loss with time at 650°C and because no "anhydro meta-xonotlite" phase seems to form, the $CaSiO_3$:H_2O ratios when using only the loss between 650°C and 850°C are too high and the true ratio is necessarily less than 6:1, very probably 5:1.

There has been some controversy over the formula for xonotlite although there is general agreement that it is probably $5CaSiO_3 \cdot H_2O$. The present data appear to confirm this value but also demonstrate the difficulties of defining water-loss for hydroxylated minerals. The suggestion that the water in xonotlite is zeolitic appears to have been disproved by these data since even heat treatment at 700°C for several hours failed to remove very much of it. The slight loss at these temperatures is to be expected considering that it is several hundred degrees above the equilibrium decomposition temperature for these pressures.

Infra-red studies.—Infra-red absorption spectra were made from the two xonotlite samples in order to obtain information on the type of bonding present in the OH^- groups. Samples were discs made by pressing 0.0037 sample dispersed in 0.2500 KBr in a mold under 160,000 psi pressure. Figure 2 is a representation of the absorption pattern thus obtained from the natural xonotlite. The pattern of the synthetic xonotlite was the same except for markedly reduced transmission. The O-H peak at 2.72 microns is very sharp, suggesting

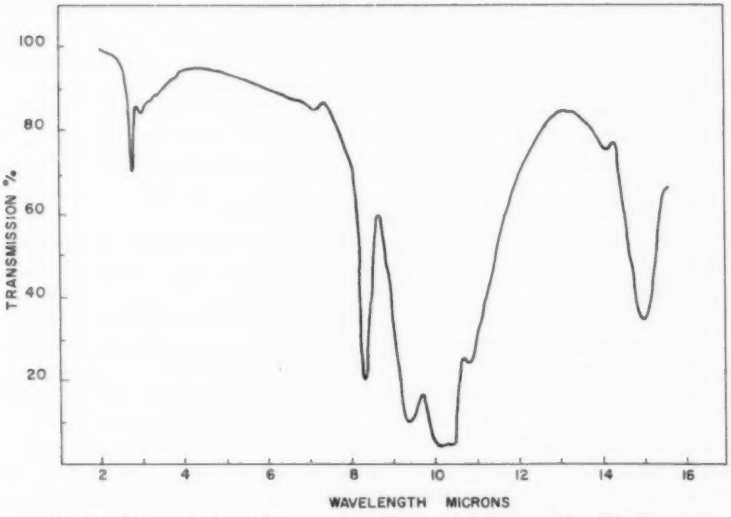

Fig. 2. Infra-red absorption spectrum of natural xonotlite using KBr discs.

a symmetrical OH ion, rather than strong hydrogen bonding usually characterized by longer wave lengths.

Calculation of Heat of Reaction.—A calculation of the heat of reaction for the xonotlite = β-$CaSiO_3$ + H_2O reaction was performed using the Clapeyron relationship and a very approximate value for dp/dt taken from the slope of the p-T curve, using 400°C at 5,000 psi and 420°C at 20,000 psi; giving ΔH = Ca.8,500 cal/mole.

A new phase: μ-(Ca,Sr)SiO_3

The μ-(Ca,Sr)SiO_3 was encountered over a wide range of temperatures (see table 4), starting principally from compositions of C2S and C5S. This phase was first encountered during the study of the system $CaSiO_3$—$SrSiO_3$ in attempt to follow the wollastonite-pseudowollastonite inversion with increasing $SrSiO_3$ content. The results of this study are reported elsewhere (Buckner and Roy, in press) and it need only be mentioned that the same phase interferes with the determination of the lower stability temperature limit of pseudowollastonite solid solutions.

This new phase may be best prepared in its pure form by crystallizing a glass of 75 percent $CaSiO_3$-25 percent $SrSiO_3$ (by weight) at 490°C and 5,000 psi H_2O pressure for a period of at least 52 hours. It is an anhydrous phase with an x-ray pattern distinct from any known strontium or calcium silicate reported in the literature, and does not match any x-ray data given in the ASTM files. It is crystallized equally well from glasses in the dry way, having no opportunity to incorporate water. X-ray data and optical properties are given in table 5.

The presence of μ-phase was noted as well in samples of C2-½S, C5S, and C7½S, and possibly in C7S. The μ-phase was produced from C2S as low as 350°C (hydrothermally), and as high as 855°C (dry). In many cases it was the only phase formed. At C2S μ-phase is probably metastable above 760°C, since it does not appear in samples treated hydrothermally above this temperature, but only β-$CaSiO_3$ and pseudo-wollastonite are present. In C5S μ-phase appears hydrothermally above about 470°C, continuing to form at least as high as 690°C, while below 470°C pseudo-wollastonite and xonotlite are formed together. Probably μ-phase has a region of stability in this system, but the data are insufficient to establish this conclusively.

In the earlier part of this study the possibility that μ-phase might correspond to para-wollastonite was considered. Optical data determined with some difficulty on the μ-phase suggested that it was uniaxial positive, in contrast to the biaxial negative character of para-wollastonite (Peacock, 1935). Powder x-ray diffraction data recently obtained for para-wollastonite (Heller and Taylor, 1956) show only very slight differences from the pattern for wollastonite, and both are clearly different from μ-(Ca,Sr)SiO_3.

The system $CaSiO_3$—$SrSiO_3$—H_2O

The data relating the effect of the addition of $SrSiO_3$ to equilibria in the system $CaSiO_3$—H_2O at low temperatures are not as conclusive as desired. However, the equilibria at various stages may be represented by the compati-

TABLE 4

Data on μ-phase

Run No.	Temp. (°C)	Pressure (psi)	Time (hrs)	Initial Condition	Result
	Composition C2-1/2S				
570	475	20,000	51	Glass	$\beta + \mu$
	Composition C5S				
571	475	20,000	51	Glass	$\beta + \mu$
	Composition C 7-1/2S				
572	475	20,000	51	Glass	$\beta + \mu$
644	500	500	45	"	$\mu + \beta$
686	695	"	182	"	$\beta + \mu$
	Composition C 25 S				
698	794	Dry	72	Glass	$\mu + \alpha$
310	855	"	65	"	$\alpha + \mu$
645	500	500	45	"	μ
679	620	"	115	"	μ
633	675	"	41	"	μ + v.l. β
109	355	2500	24	"	μ
261	394	5000	70	"	Xon + μ
180	455	"	48	"	μ
36	758	"	29	"	$\alpha + \beta + \mu$
613	490	20,000	117	"	$\beta + \mu$
	Composition C 50 S				
646	500	500	45	Glass	$\mu + \alpha$
634	675	"	41	"	α + little μ
688	695	"	182	"	$\mu + \alpha$
675	472	20,000	142	"	μ

bility triangles of figure 3. These represent the crystalline phases believed to exist in equilibrium at a constant pressure of 10,000 psi H_2O at the given temperature.

The first triangle represents the temperature region where tobermorite is stable, and it is expected that a small amount of Sr^{2+} may substitute for Ca^{2+} in the structure, hence the representation of the solid solution area. No hydrate of $SrSiO_3$ is known to exist even at these relatively low temperatures, and α-$SrSiO_3$ apparently exists in equilibrium with H_2O. Triangle 2 represent the region where tobermorite is no longer stable, but xonotlite, and Sr-bearing xonotlite are formed. Triangle 3 is above the stability limit of pure xonotlite, where β-$CaSiO_3$ is stable and represents the fact that Sr-bearing xonotlite solid solutions are stable to higher temperatures than $5CaO \cdot 5SiO_2 \cdot H_2O$. Triangle 4 represents equilibria above the stability limit of all hydrates, and suggests that the new phase, μ-$(Ca,Sr)SiO_3$ is stable at intermediate Ca, Sr ratios, while β-$CaSiO_3$ and α-$SrSiO_3$ solid solutions are stable at the extremeties. The last triangle represents equilibria at higher temperatures where the μ-phase is no

Abbreviations: β = β-$CaSiO_3$, μ = μ-(Ca, Sr)SiO_3; α = pseudo-wollastonite; compositions given in wt. % $CaSiO_3$ (C) and $SrSiO_3$ (S).

TABLE 5

X-ray Data on μ-(Ca,Sr)SiO_3

(Composition C25S)

2θ	d	Height	Rel I
17.5	5.06	10	16
25.2	3.53	9	14
28.0	3.18	20	30
29.15	3.06	50	74
29.9	2.988	6	9
30.4	2.940	68	100
33.5	2.674	12	8
34.05	2.633	27	40
34.9	2.570	8	11
39.8	2.264	6	9
40.9	2.206	10	16
42.15	2.143	6	9
43.6	2.075	12	8
46.0	1.972	6	9
49.8	1.830	8	11
51.8	1.764	7	10
54.7	1.677	6	9
62.5	1.486	6	9

Optical Properties of μ-(Ca,Sr)SiO_3

Under the microscope the appearance of μ-phase is that of aggregates of radiating fibrous crystals. The fibers are oriented length slow. The best interference figures indicate that the material is uniaxial positive:

μ-Phase (C25S)
$n_E = 1.630 \pm .002$
$n_O = 1.623 \pm .002$
μ-Phase (C50S)
$n_E = 1.650 \pm .002$
$n_O = 1.639 \pm .002$

longer present, and β-$CaSiO_3$ and α-$SrSiO_3$ solid solutions are the only phases stable in equilibrium with H_2O. At still higher temperatures (above 1120°C) only α-(Ca,Sr)SiO_3 solid solutions are stable.

DISCUSSION AND CONCLUSIONS

As in many hydrothermal studies, the equilibrium decomposition temperature of a particular hydrate has been found to be considerably lower than would be suggested by the nearest approach to equilibrium on dehydration at atmospheric pressure. A maximum temperature of about 425°C is suggested by the present data for xonotlite associations in contact metamorphic bodies formed at moderate pressures. Solid solution may have some effect on the stability of xonotlite, as demonstrated by the increase in decomposition temperature of Sr-bearing xonotlite. However, xonotlite is usually quite pure, and although one variety has been reported which contains up to 1:7 Mg:Ca

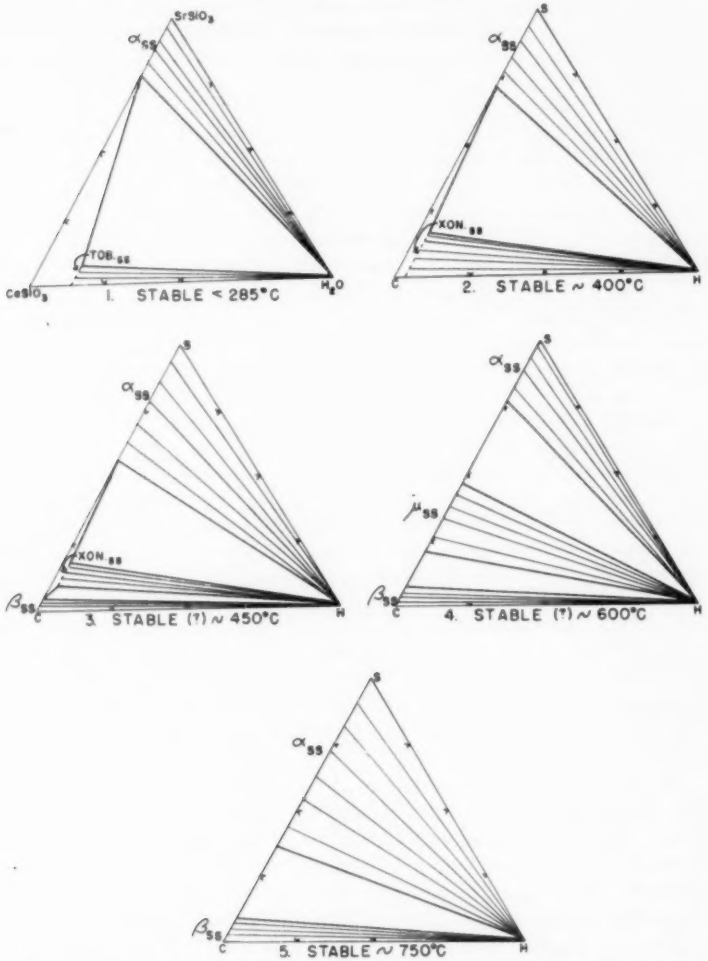

Fig. 3. Compatibility triangles showing probable equilibria in the system $CaSiO_3$—$SrSiO_3$—H_2O at a pressure of 10,000 psi at certain representative temperatures. Tob_{ss} = tobermorite solid solutions; α_{ss} = α(Sr, Ca)SiO_3 solid solutions; β_{ss} = β(Ca, Sr)SiO_3 solid solutions.

(jurupaite) (Taylor, 1954), the Mg^{2+} ion is smaller and may not have as great an effect on the stability as the Sr^{2+} ion.

Tobermorite, though found in several states of hydration, is probably stable only in the 11.3 Å modification throughout the p-T range of the present study. This agrees rather well with observations on the natural mineral such

as those of McConnell (1954) which suggest that the 14 Å hydrate is gel-like and very easily dehydrated. The maximum stability temperature of about 285°C for tobermorite having $CaO:SiO_2$ ratios of 4:5 to 5:5 would certainly be an upper limit to the stability of a tobermorite phase in the $CaO—SiO_2—H_2O$ system. Tobermorite-like phases are formed from cement materials of considerably higher CaO content at lower temperatures. However hillebrandite and C_2SH_2 are formed (apparently) stably from these same compositions at least as low as 200°C. An effective temperature for autoclaving cement block to produce the tobermorite phase would therefore also have to be kept below this latter limit. Furthermore, compositions near the 1:1 $CaO:SiO_2$ ratio when treated hydrothermally near the upper stability limit of tobermorite tend to react readily with CO_2 and form scawtite, or "CSH(A).

The sluggishness of the conversion of tobermorite to xonotlite hydrothermally is notable. Although at first it was thought that an intermediate phase was formed, similar to the 9 Å tobermorite formed on atmospheric pressure dehydration, later evidence suggests that the phase encountered is most probably scawtite formed through slight contamination with CO_2. The rearrangement of tobermorite having a $CaO:SiO_2$ ratio of 4:5 (or 5:6) to produce xonotlite necessitates a migration out of SiO_2 or other local readjustment of composition, which is expected to be difficult to bring about at the relatively low temperature of the equilibrium decomposition. Indeed it is true that 5:5 tobermorite reacts somewhat more readily to yield xonotlite, but little is known about the structure of 5:5 tobermorite. At atmospheric pressure 11 Å tobermorite dehydrates (via the 9 Å structure) directly to wollastonite (Taylor, 1959b) which was shown to take place with a rather simple rearrangement, and furthermore at a much higher temperature. The structures of tobermorite (Megaw and Kelsey, 1956) and xonotlite (Mamedov and Belov, 1955) would suggest no simple conversion relationship, although Taylor (1959b) has shown that single crystals of tobermorite on hydrothermal treatment will yield oriented aggregates of xonotlite.

The production of the new phase, μ-$(Ca,Sr)SiO_3$ in the system $CaSiO_3—SrSiO_3$ illustrates the formation of a new structural modification at low temperatures where thermal movement is apparently not great enough to provide accommodation of the ions in the established structures. $SrSiO_3$ clearly prefers the pseudo-wollastonite structure, whereas the wollastonite structure can only accommodate a very limited amount of $SrSiO_3$. Therefore, instead of the usual exsolution phenomena observed when extensive solid solution is no longer possible, an entirely new structure is formed which can apparently accommodate both ions in varying amounts. However, further data would have to be obtained to define a stability region for the new phase.

The possibility that μ-$(Ca,Sr)SiO_3$ may correspond to an un-named mineral found at Skye (Tilley, 1950) was suggested by Tilley (personal communication). The mineral, found as narrow border zones separating a quartz core from a zone of radiating wollastonite crystals, had optical properties very similar to those of μ-phase: fibrous, $n_\alpha = 1.620$, $n_\gamma = 1.628$, + elong, apparently uniaxial +. The pressure-temperature conditions for formation of the

mineral may be similar to those suggested for the μ-phase, i.e., moderate, definitely not a low-temperature hydrothermal association.

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A STAINED SLICE METHOD FOR RAPID DETERMINATION OF PHENOCRYST COMPOSITION OF VOLCANIC ROCKS

PAUL L. WILLIAMS

U. S. Geological Survey, Denver, Colorado

ABSTRACT. In recent stratigraphic studies of Tertiary ignimbrites in the Great Basin, correlation of units by distinctive lithologic features is independently verified by quantitative study of phenocrysts. The relative abundance of six mineral groups can be readily evaluated by area counts, with a binocular microscope, of etched and stained rock slices. The method obtains results rapidly and with sufficient accuracy to confirm field correlations, as is demonstrated by phenocryst study of four tuffs comprising the Quichapa formation.

INTRODUCTION

In the stratigraphic studies of Great Basin ignimbrites outlined in the preceding companion paper by Mackin, correlation is based primarily on distinctive lithologic features of individual units and similarity in sequence of a number of units. It was evident early in the investigation, however, that there was need for an independent method of identifying the units, particularly in areas where the lithology is blurred by alteration effects, and where stratigraphic and structural complexities make it impossible to depend on similarity in sequence.

Hand lens examination in the field and petrographic study of thin sections indicated that the mineralogy of the phenocryst assemblage would serve as a good check on correlations in most instances. But "hand lens mineralogy" is inadequate for distinguishing between certain of the ignimbrites, and does not provide the quantitative data needed for an objective statement of the basis of correlation in cases where identification of the ignimbrite depends on the percentages of the minerals present. Thin section study yields petrographic data not obtainable by other methods, but has the disadvantage that both preparation and study of the sections are rather slow. Moreover, especially in rocks with sparse phenocrysts, several standard size thin sections are required for a reasonably accurate evaluation of the phenocryst composition.

The stained slice method presented here was developed in response to a need for a method of evaluating the phenocryst composition of the ignimbrites (a) with sufficient accuracy for use in correlation, and (b) rapidly enough to make the data for a large number of specimens available promptly and without undue cost in time. The importance of rapidity is suggested by the fact that a single field season of work in the volcanics by members of the University of Washington group yields several hundred specimens requiring analysis of the phenocryst composition; more than 2500 specimens have been studied to date. If the specimens are handled in groups of 20 or more, and no special problems of identification are encountered, the whole procedure described here, from sawing of the slices to drafting of the histograms used to express the phenocryst composition, requires only about 20 minutes per specimen, most of which is spent in examination with the microscope.

This note is an outgrowth of work as field assistant to J. H. Mackin and E. F. Cook in the Great Basin during the 1955 field season, and laboratory study of specimen collections as a temporary employee of Gulf Refining Corporation. I am indebted to H. R. Blank and W. R. McCarthy for data on the volcanic sequence in the Bull Valley and Gunlock-Motoqua areas, and to Blank, Mackin and D. L. Schmidt for critical reading of the manuscript.

LABORATORY PROCEDURE

(1) A flat slice five to ten millimeters thick is sawed from the hand specimen. Four or five centimeters square is a convenient size.

(2) The slice is polished on a lap with no. 220 Carborundum. Polishing removes the saw marks and provides an even surface for staining. In the sawing and polishing of lightly welded and non-welded rocks, quartz and other phenocrysts tend to be plucked from the matrix. Plucking is prevented by impregnating the slice before polishing in a 10:1 xylene-canada balsam solution and heating until the balsam is thoroughly cooked.

(3) After the slice has dried thoroughly at room temperature, the polished surface is immersed for one second in 48 percent hydrofluoric acid, and blotted immediately on absorbent paper. The slice is placed face up and allowed to dry thoroughly.

(4) After drying, the slice is immersed in sodium cobaltinitrite solution for thirty seconds. It is then washed immediately in cold water to remove the excess stain, and allowed to dry face up. The staining technique is adapted from a method first described by Gabriel and Cox (1929). The stain solution is prepared by mixing, by weight, three parts of sodium cobaltinitrite powder with five parts of distilled water. Because the solution decomposes with age, it must be renewed every few weeks.

The stained slices are ready for study as soon as thoroughly dry. A binocular microscope is recommended; a magnification of nine to twelve diameters is sufficient for most rocks.

The five or six minerals or mineral groups that occur most frequently in the Great Basin ignimbrites can be quickly identified in the etched and stained slices by an experienced analyst. Crystal form is helpful but it is less distinctive than it would be in ordinary igneous rocks because many of the phenocrysts in ignimbrites are broken fragments.

Quartz phenocrysts appear as glassy, unstained and virtually unetched grains ranging from colorless to very dark, smoky varieties.

Before the acid treatment the feldspars are seen as clear grains that can be distinguished from quartz only under favorable circumstances by shape and cleavage. A coating produced by the acid remains white on plagioclase while that on sanidine is stained yellow by the sodium cobaltinitrite solution.

Because of the potassium in biotite, the usual black or dark green color of the mineral is modified by the stain to a yellowish green. The color change is less apparent on cleavage faces than on sections of the mineral cut across the cleavage.

The pyroxenes and amphiboles are identified chiefly on the basis of grain shape, cleavage, and color. Etch and stain effects are useful in distinguishing

between these groups, but the criteria differ depending on the varieties present and on the freshness of the grains, and need not be spelled out here; each analyst will discover for himself ways of identifying the mineral types that characterize a given suite of rocks.

In dealing with the mafic minerals and to a lesser extent with the quartz and feldspar, it is advisable at the outset to cross check the binocular identifications by examination of the same minerals in oils or in thin sections.

The percentages of each phenocryst type are estimated with the aid of a transparent glass plate ruled in a 10 by 10 millimeter grid containing 100 squares. The grid is placed directly on the stained surface, and the analyst mentally "forces" the irregularly shaped grains to fill the grid squares. The use of a grid for percent estimation was first described by Williams (1905).

It seems to be well established that the area occupied by a given mineral component on a random plane surface cutting a rock is directly proportional to the volume of that mineral in the rock (Chayes, 1954, and works cited therein). This point is worth mention, but it is not critical for present purposes because the percentage estimates do not purport to represent quantities in an absolute sense; the estimates are only for comparative purposes, to be compared to percentages of the same minerals estimated in the same way in other volcanic units. It should be noted in this connection that the identity of mineral grains smaller than ¼ millimeter may be obscured by spread of the coating formed by the hydrofluoric acid. For this reason and because of the low magnification, neither the percentages of phenocrysts relative to groundmass nor the percentages of the individual minerals are necessarily comparable with percentages based on study of thin sections with a petrographic microscope.

In an effort to evaluate the reproducibility of the percent estimates, herein called probable error, a number of slices have been re-examined by the writer after a lapse of time, and by other analysts currently working with the Great Basin volcanics. The results indicate that the probable error is of the order of 10 percent for the more common mineral constituents in the average rock. The probable error is considerably greater for very small grains because of the difficulty of estimating their areas relative to the area of the grid squares. In tuffs with 25 percent or more of phenocrysts five different fields are examined, so that the estimates of mineral percentages are based on at least 125 grid squares "occupied" by phenocrysts. In dealing with tuffs with smaller percentages of phenocrysts a larger number of fields are examined, up to the limit allowed by the size of the slice. In some rocks with very small amounts of phenocrysts the number of "occupied" squares is as small as 25, and the probable error increases accordingly.

Point counting (Chayes, 1949) is more accurate than area estimates controlled by a grid, and there are other ways to reduce the limits of error of the technique, but their use defeats the purpose of the method, which is to make quickly available mineralogic data accurate enough to serve as a check on field correlation. In general the probable error in estimates based on a single stained slice of a given tuff is of the same order of magnitude as the actual mineralogic

variation between specimens taken from different parts of the same outcrop of that tuff.

CORRELATION OF THE QUICHAPA FORMATION

Figure 1 consists of a number of columnar sections in which the phenocryst composition of the tuffs comprising the Quichapa formation is expressed by histograms. The histogram columns are arranged to show the correlation of the Quichapa members in an east-west belt across southwestern Utah and southeastern Nevada.

As indicated in the legend, the white bar on the right side of each histogram indicated the total amount of phenocrysts in the rock. The remaining bars represent the percentage of each of the major mineral groups with respect to the total volume of phenocrysts. For the sake of compactness all of the mafic minerals are plotted in the same bar; pyroxenes are shown by a diagonal line pattern, biotite in solid black, and amphiboles by vertical lines. If all three mafic groups are present in amounts that can be plotted, the arrangement is, from top to bottom, pyroxene, biotite, amphibole, regardless of their relative abundance. Trace amounts of a mineral are indicated by a short vertical line in the middle of the appropriate bar; in the mafic bar trace amounts of amphibole are indicated by a solid line, biotite by two dashes and pyroxene by three dashes. In our work sheets the histograms are accompanied by symbols, letters, or numbers expressing "degree of welding", proportion of lithic fragments and/or pumice, distinctive heavy minerals, index of refraction of the glass, thickness of the unit, and other properties bearing on correlation, but these are omitted in figure 1 because they involve problems of quantification and other questions which need no discussion here.

The four members comprising the Quichapa formation are defined and described in the preceding paper by Mackin (1960). The Harmony Hills tuff is a crystal-rich ignimbrite wholly different in lithology from the other Quichapa units. The Bauers tuff and Swett tuff are vitric ignimbrites, nearly identical in lithology, distinguishable on the basis of the presence or absence of sanidine—the contrast is strikingly shown by the histograms. The Leach Canyon tuff is characterized by conspicuous lithic fragments. It seems to contain two distinct phenocryst suites, one with about equal amounts of quartz and sanidine, and the other with a notable excess of quartz over sanidine.

The Leach tuff is present in the Swett Hills; a histogram for the unit at this locality is absent on figure 1 because the number of specimens available for study was inadequate. The absence of the Swett tuff in the Gunlock, Bull Valley and Pine Valley areas, and of the three upper Quichapa members at Isom Ranch and Brian Head, is probably due to non-deposition rather than to erosion.

As indicated by Mackin, correlation of the Quichapa ignimbrites from Brian Head to the narrows of the White River was based originally on the lithology of the individual units and especially on the similarity in sequence of the units in section after section. The phenocryst composition, determined from stained slices and expressed by histograms as in figure 1, serves as a valid criterion for confirming the correlations.

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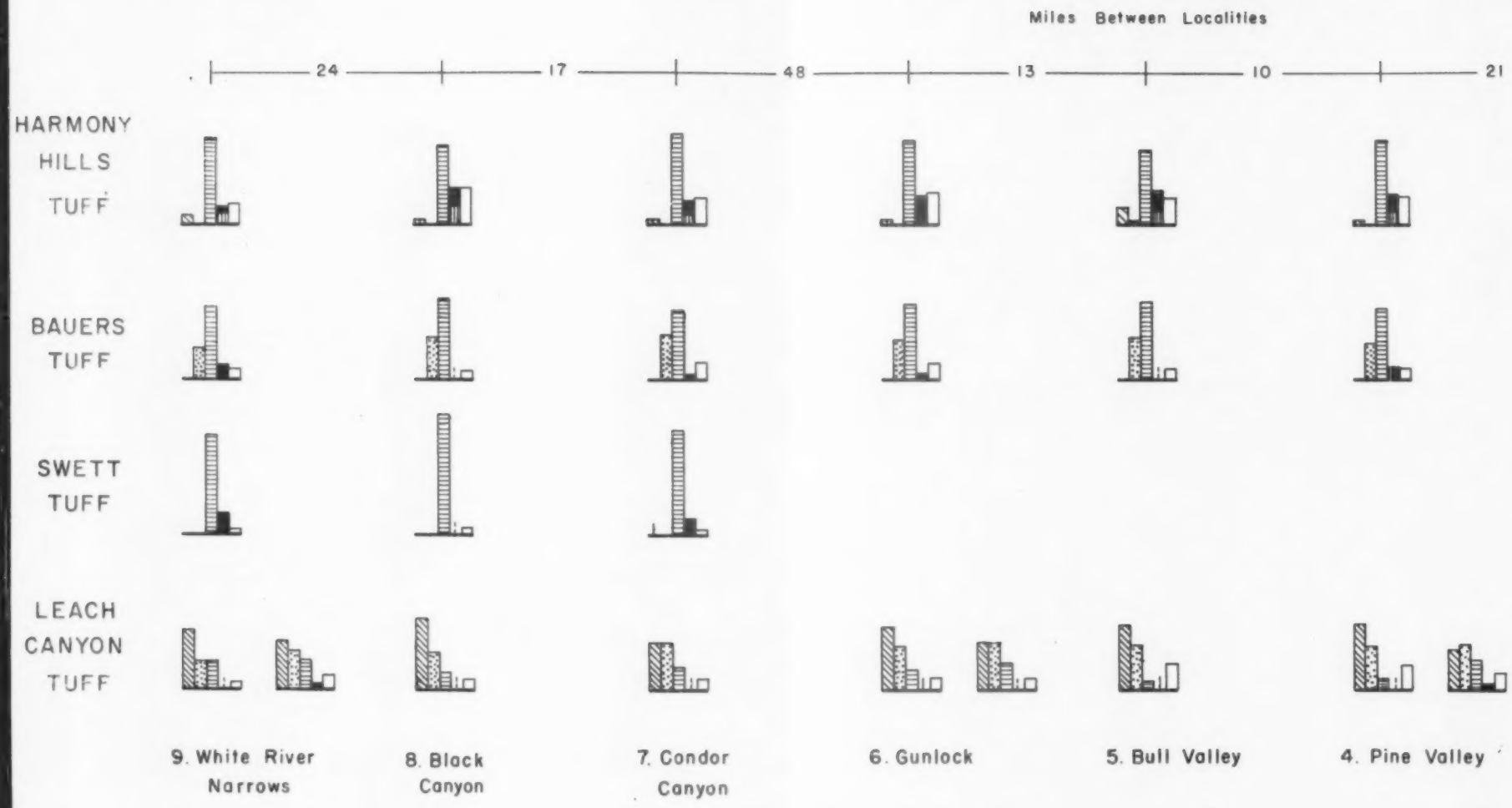
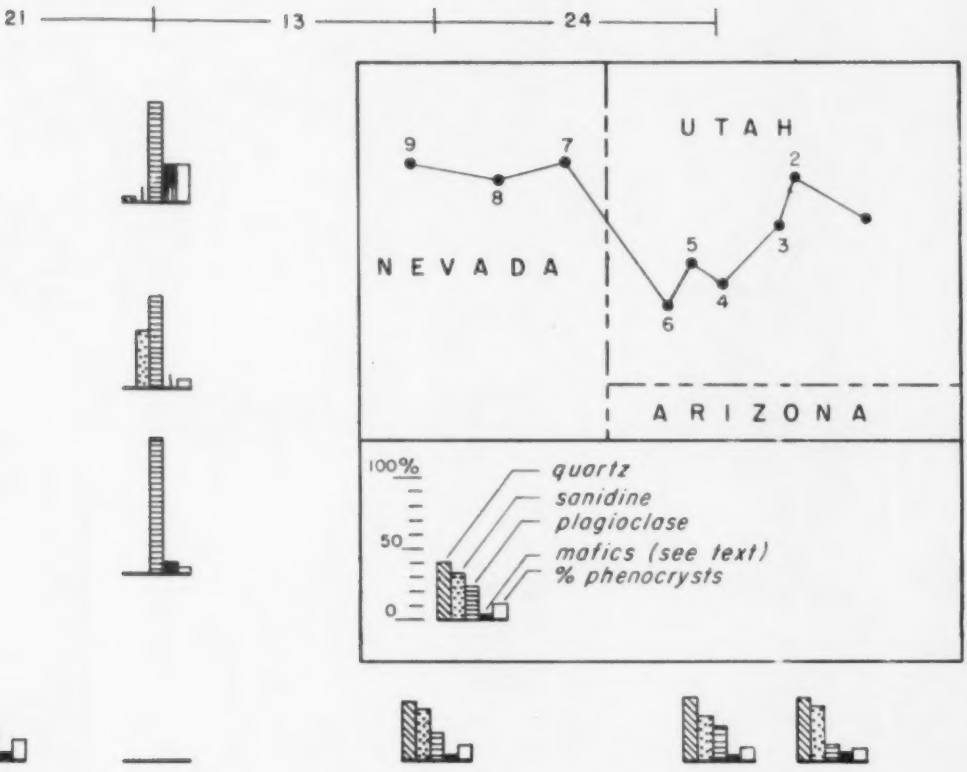


FIGURE 1 - PHENOCRYST COMPOSITION OF THE QUICHAPA F


21
13
24
U T A H
N E V A D A
A R I Z O N A
9
8
7
6
5
4
3
2
100%
50
0
quartz
sanidine
plagioclase
mafics (see text)
% phenocrysts
3. Swett Hills
2. Isom Ranch
1. Brian Head

FORMATION

COMMUNICATION

SOME MINERALOGICAL EQUILIBRIA IN THE SYSTEM K_2O—Al_2O_3—SiO_2—H_2O

In a recent article by J. J. Hemley (this JOURNAL, v. 257, p. 241-270, 1959) on page 266 the exponents were omitted from the equilibrium expression. For the reaction as given in the text, $K = \dfrac{a^{1/2}\text{mica}\ a\text{K}^+}{a^{3/2}\text{K-feldspar}\ a\text{H}^+}$.

The constant corresponding to this overall expression is fixed, although the $^a\text{K}^+/^a\text{H}^+$ value changes with change in composition of the solid phases.

On page 259 the dissociation expression for HCl should be

$$K_{HCl} = \frac{a_{H^+}\, a_{Cl^-}}{m_{HCl} - \dfrac{a_{H^+}}{0.1}} = 7.0 \cdot 10^{-3}.$$

As shown, the mean activity ratio of KCl/HCl is then $\dfrac{a_{H^+}}{a_{K^+}} = 10^{2.89}$.

J. JULIAN HEMLEY

REVIEWS

Introduction to Historical Geology; by RAYMOND C. MOORE. P. ix + 656, numerous illustrations. New York, 1958 (McGraw-Hill, $7.95).—This second edition of a widely used text is much expanded and extensively revised. The changed format, increased page size, and profuse (over 600) illustrations combined with Moore's masterful presentation make it a very attractive book. The end papers—showing the stratigraphic distribution of the major groups of organisms in front, and a colored geologic map of Europe in back—add much to the attractiveness. Notable in this day and age is the price—$7.95. The publishers are to be commended for presenting such a profusely illustrated book at this low price.

The general plan of the book is the same as in the first edition, with one chapter added (total 21 chapters) to compensate for a changed classification of the Cenozoic. The book considers, in sequence: materials and methods; evolution of life; the Precambrian—here termed the Cryptozoic Eon; the successive geologic periods of the Paleozoic, Mesozoic, and Cenozoic Eras, with chapters on the nature and evolution of life at the end of each era; and finally, the geologic record of man. A feature of special merit is the addition of a list of selected "Readings" and a series of "Questions" at the end of each chapter. These, together with the lucid presentation of factual data and the demonstration of methods of arriving at principles of interpretation, make this a very useful book. The single appendix of the original edition is greatly changed and altered to a section on "Characters of Organisms Represented among Fossils", and two additional appendices, "Lithologic Symbols for Geologic Sections" and a "Glossary" are added. These changes greatly enhance the value of the book.

Like other contemporary American texts in this field, the book is centered on North America and only occasionally does it touch on the geological events

of the other continents. In the age of jet planes and mass travel to the far corners of the earth this provincialism of American authors is regrettable.

Many of the illustrations are new and all are outstanding. The geologic maps, showing the outcrop and probable subsurface distribution in the United States of the rocks of each system are a distinct improvement over the prior paleogeographic maps. It is to be hoped that in the future an indication of maximum and minimum extent of marine sediments may be added to them. Another noteworthy improvement is the addition of a plate of selected graphic columnar sections for each system. As is nearly unavoidable, a few errors have crept into these sections. Particularly notable to a West Coast geologist is the omission from both the Jurassic and the Cretaceous, of the bothersome but nevertheless significant Franciscan-Knoxville complex from the section for California. Likewise only the lower part of the Upper Cretaceous is indicated as present in California when the late Upper Cretaceous is very well developed and widespread. Additionally, like many other "outsiders" the author, in his chapters on the Paleogene and Neogene, seemingly got lost in the intricacies of the divergent marine megafaunal and microfaunal Cenozoic chronologies of the Pacific Coast and "lost" a significant portion of the California mid-Cenozoic section.

Another innovation, and to this reviewer at least, one to be lamented, is the discarding of the Tertiary and Quaternary periods on the grounds of inappropriateness and the utilization instead, of Paleogene and Neogene, commonly used in Europe, as the two periods of the Cenozoic. Moore, in contrast to European usage, extends the Neogene, a term originally proposed by Hoernes as a substitute for Miocene and Pliocene, to include the Recent. He seemingly has not realized that most who use these terms employ the Tertiary (limiting the Neogene to the Miocene and Pliocene) and Quaternary as Eras and do not use Cenozoic. Instead of promoting a standard nomenclature (which is the only justification for the use of these terms) Moore's usage adds to the confusion.

In discussing the highly elevated (1300 feet or more) late Pleistocene marine terraces of the California coast, Moore (p. 477) suggests that they represent "different levels of the sea itself" rather than crustal upwarping. Elsewhere he recognizes a lowering of sea level of 350 feet or more. These totals add up to a total variation of sea level during the Pleistocene of over 1600 feet! It does not seem probable that the implications of this conclusion were seriously considered.

Moore (p. 479-481) discusses the San Andreas fault of California and unqualifiedly accepts Hills' estimates of very large lateral movement (over 320 miles since the Cretaceous) along it. Admittedly the San Andreas is a notable fault but Hill's conclusions are far from being well documented or accepted and the necessary corollaries have not been explored.

A few other points in the book need attention. The base of the Cambrian system is placed (p. 109, 113) at the " . . . first major break in sedimentation beneath the lowest known Cambrian fossils.", yet in the glossary "system" is defined as the rocks formed during a period, which in turn is defined as a major division of geologic time. The boundaries of a span of time are not

variable as this usage would imply, but synchronous. The term "cyclothem" is defined in the glossary but not used in the text in connection with the mid-continent Pennsylvanian cyclic sediments for which the term was originally proposed. The "*Glossopteris* flora" is briefly described (p. 275) but its well known and widely used name is not applied to it. The term "syntopogenic equivalents" is introduced (p. 21) for rocks "formed in like places or manner." Introduction of such a formidable phrase in an introductory text does not seem justifiable.

Overall this is an outstanding text for introducing students to the historical geology of North America and for illustrating principles. It is to be highly recommended.

J. WYATT DURHAM

Explanatory Text for Preliminary Geological Map of Connecticut, 1956; by JOHN RODGERS, ROBERT M. GATES, and JOHN L. ROSENFELD. P. 64; 3 figs., one with folded map in pocket. Storrs, 1959 (Connecticut Geological and Natural History Survey, Bull. No. 84).—The geological map, published three years earlier than the explanatory text, is on a plane base, scale about 4 miles per inch, with political boundaries, place names, and road net in dark lines; geologic boundaries, fault traces, and letter designations of bedrock units in red. One overprint pattern in red covers a few small areas. Margins of the map contain adequate explanatory legend, and on the back of the sheet are printed brief descriptions of the bedrock units, with a sketch map assigning credit to geologists whose work supplied material used for specified areas. Explanatory text in the bulletin states in detail the sources for the map; gives an overall analysis of structural and stratigraphic relations in the bedrock, with recognition of two provinces older than the distinctive Triassic units; and presents more detailed descriptions of formations than those printed on the map sheet. At the end of the text is an extensive list of references, with asterisks indicating the publications actually used in compiling the map.

The first statewide study of geology in Connecticut was made by the scientist-poet James G. Percival, starting in 1835, a pioneer date for geologists marked by founding of the Geological Society of London. Percival's geologic map and accompanying text of 495 printed pages, published in 1842, are a truly remarkable accomplishment. All later students of the area have been impressed by the accuracy with which Percival mapped and described the complex bedrock, though his equipment was primitive by modern standards. Improvements have come slowly, as growth of the science has brought better understanding of rock types and of field relationships. The next major advance in Connecticut came with the detailed study by W. M. Davis of the Triassic rocks, published in 1898. Founding of the present State Geological Survey a few years later stimulated field studies, climaxed in 1907 by publication of *Preliminary Geological Map of Connecticut*, on which all bedrock units are represented in color. This title, repeated verbatim on the new map that embodies results won during another half century, emphasizes continuing recognition by field workers that the complex bedrock still is an inviting field for research.

Continued study has established relative ages of many metamorphosed sedimentary bodies, though lack of fossil evidence makes impossible a confident geologic dating of some important units. By recent cooperative efforts some of the formations in the eastern Connecticut province have been traced with assurance into firmly dated units in Massachusetts and New Hampshire. Radiogenic dates supplied by pegmatites east of the Triassic belt are notably consistent, though doubts remain in assigning these dates to any specific orogenic event.

The new map represents definite advances in knowledge of Connecticut geology. Recent completion of large-scale, highly accurate base maps covering the state is attracting young geologists into detailed studies, giving promise of a geologic map of Connecticut, in the not too distant future, with its title not qualified as preliminary. CHESTER R. LONGWELL

Géologie de l'Uranium; by MARCEL ROUBAULT. P. xi, 462; 205 figs. and maps, 2 colored plates, 9 tables. Paris, 1958 (Masson et Cie, Editors, 6,000 fr., paper bound 5,200 fr.).—In 1948, M. Roubault was appointed Director of the Atomic Energy Commission of France in charge of investigations of uranium prospects. He is, therefore, well equipped to write on the subject of the geology of uranium. In fact, M. Francis Perrin states in the preface to the book that M. Roubault, in addition to being a competent geologist, gained vast experience in organizing and directing the exploration and search for uranium deposits in France and Africa as well as serving as overseer of the mining of several important deposits.

The book is divided into three parts. The first part consists of 116 pages of generalities pertaining to the identification of radioactive minerals (with 12 color photographs), describes prospecting methods and equipment, and lists Everhart's all-encompassing classification of uranium deposits. The second and most interesting part consists of 276 pages of descriptions of the "principaux gisements uranifères du monde." Almost 30 percent of this section, as one should expect, pertains to uranium deposits of France. The remaining deposits of the world are very briefly described, although some are done concisely with the aid of numerous rather good to excellent maps, cross-sections, and block diagrams. The deposits are grouped for description under six geographic areas, viz., (1) Central Europe, (2) Eastern Europe including the Balkan states, Eastern Russia, and Norway and Sweden, (3) North and South America, (4) South Africa, (5) "Autres Régions D'Afrique" and (6) Asia and Australia. The bibliography is adequate but very few references are later than 1956 and almost all are readily available in most libraries. The third section of the book contains the conclusions; i.e., data on the reserves of uranium and thorium, and an appendix. The reserve figures are given as of about 1956. M. Roubault's figure for U. S. reserves does not include Wyoming reserves; his figure for the reserves for Canada, 180,000 metric tons of U_3O_8 (not U, as Roubault indicates) should be at least doubled or tripled just for Blind River. With estimated reserves of about 250,000 metric tons of U_3O_8 for South Africa, M. Roubault's figure of 10,000 tons is not even comparable.

An alphabetical index of authors cited, uraniferous minerals, and a geographical index are also included.

In conclusion, M. Roubault has summarized a vast amount of information, enabling him to describe rather tersely almost all the known relatively important and even unimportant uraniferous deposits of the world.

MEAD LEROY JENSEN

Karta över Sveriges jordarter; scale 1:1,000,000; in 3 sheets. Stockholm, 1958 (Sveriges Geologiska Undersökning, ser. Ba, no. 17, in 3 sheets, 15 kronor per sheet).

Description to accompany the map of the Quaternary deposits of Sweden; by G. LUNDQVIST. P. 116. Stockholm, 1959 (Sveriges Geologiska Undersökning, ser. Ba, no. 17, 5 kronor).—This fine piece of work is the first map of the surficial geology of Sweden to be published on a scale as large as 1:1 million. It is largely a compilation from a large number of local maps on various scales but also includes data here published for the first time.

The principal units represented include till, glacial-lake clay, eskers and deltas, sandy sediments, fine sediments, bog sediments, and exposed bedrock. The intricacy of detail represented by the last category gives a good picture of the detailed character of much of the source information.

The map is an incomparable reference source for the surficial deposits of Sweden. It is clearly printed, there are plenty of place names for reference, and the colors are well selected to stand out in contrast.

The value of the map is enhanced by the accompanying paper (in English), one part of which describes each class of sediment, and discusses some of them in considerable detail. This part makes a good condensed textbook on the surficial geology of a glaciated region. Another part is a systematic presentation of natural regions of Sweden based on character of surficial material. Both parts are generously illustrated with photographs and sketch maps. The book and maps are a must for scientists interested in surficial geology and visiting Sweden in the Congress year 1960; no doubt they were published in time to be useful in just this way.

The map fits nicely the 1:1,000,000 map of the glacial geology of Norway by Olaf Holtedahl and Bjorn Andersen (Norges Geologiske Undersökelse, no. 164, Oslo, 1953, pl. 16). The accompanying Norwegian text by Professor Holtedahl (idem, p. 585-1118) also is an informed and comprehensive discussion of the surficial geology of Norway, in far more detail than the Swedish volume. The Norwegian publication is another essential for scientist visitors to Norway in the Congress year.

R. F. FLINT

Subsurface Geology in Petroleum Exploration; a symposium edited by JOHN D. HAUN and L. W. LEROY. P. 887, many text figures. Golden, Colorado, 1958 (Johnson Publishing Company, $10.00)—The editors of this symposium —modeled after the now familiar *Subsurface Geological Methods*, compiled by L. W. LeRoy—have set as its objective the familiarization of the "student, the practicing petroleum geologist, and the petroleum engineer with the tools and

techniques used in the search for new oil and gas pools." In realizing this objective they have been successful to an amazing degree. The scope of the book is broad, the coverage of the individual subjects essentially complete, and the technical competence of the contributors unquestioned. Several of the chapters published in *Subsurface Geologic Methods* have been transferred intact, others have been revised to include recent developments. New chapters have been added to cover Thermoluminescence Analysis, Permeability Surveying Methods, Continuous Velocity Logging, Magnetic Well Logging, Stereographic Problems, Gravity and Magnetic Effects of Subsurface Bodies, Turbine Drilling, Jet Bits, and Exploration Planning.

Opinion among readers will certainly differ as to the relative importance and proportion of space assigned each subject. For example, subjects as fundamental and repeatedly referred to as Stratigraphic Correlation and Micropaleontological Analysis receive equal or less detailed coverage than Differential Thermal Analysis and Thermoluminescence Analysis—both important processes, but highly specialized and less frequently referred to. The limited space allotted the chapters on micropaleontology and stratigraphic correlation has to some extent impaired their over-all usefulness for they contain little or no discussion of the reliability or weaknesses of the various methods of correlation.

The value of the new chapter on Gravity and Magnetic Effects of Subsurface Bodies to the practicing petroleum geologist or engineer is debatable. The paper contains an extended mathematical consideration of gravitational and magnetic force fields but nothing concerning the geologic significance and application of data derived from gravity-magnetometer surveys.

The final chapter, a new paper on Exploration Planning, is of particular interest. It serves to bring together in a single composite picture the widely varied exploration methods and basic thinking processes which have often been successfully used in evaluating and exploring a potential oil province.

The few shortcomings of the book discussed in this review do not seriously detract from its over-all merit. It will certainly become a standard reference for petroleum geologists and engineers as well as a text for subsurface geology.

R. W. POWERS

Cours de Géomorphologie, Part 1, Géomorphologie Structurale; Volume 2, Géomorphologie des régions; Part 1, Les massifs anciens des plateformes; by ANDRE CAILLEUX and JEAN TRICART. P. 252. Paris, 1957 (Centre de Documentation Universitaire).—Everyone knows that European geography is interpreted differently from North American. But we were unprepared for the remarkable contents found in the standard Sorbonne Geomorphology course. This review only treats with a single number of a series that runs to several volumes. Its most striking feature is the highly analytic geotectonic approach: in short, it is more of a regional and world structural geology than a pure geomorphic study.

Chapter I (p. 1-34) deals with the structural (i.e. geotectonic) characteristics of the great platform (cratonic) regions, leading out from a particular example, the genesis of the Paris Basin and its borders; and then to funda-

mental generalizations on the subject (dominance of vertical movements, rates of movement, times of epeirogenic revolution).

Chapter II (p. 35-124) considers the geomorphology of the crystalline shields. From methods (profiles, statistical analyses, paleogeography, etc.) the older cyclic theories of W. M. Davis and Baulig are compared with the newer concepts of detailed paleogeographic reconstruction.

The structural character of the shields is seen under the influence of lithologic forces (notable metamorphism), and of tectonic forces (faults and warping), developing a distinct morphogenetic classification. The Russian term *anteclise* is adopted—meaning a broad stable upwarp, the opposite of a *syneclise*, a broad downwarp corresponding essentially to an autogeosyncline in the terminology of Kay; there is no direct English equivalent of anteclise, and it rather looks as if this term is destined to become adopted into the literature with the inevitable typographic confusion with "anticline".

Chapter III (p. 125-187). Sedimentary basins are treated next, but only those superimposed upon the relatively stable foundation of what Kay calls the "hedreocraton". The geomorphology is seen as a product of the character of the sediments, the latter in turn being greatly dependent upon the movements in the tectonic framework. A detailed classification of sedimentary basins is offered, essentially structural.

Chapter IV (p. 188-245) handles in detail every class of shield, intermediate platforms, smaller blocks and massifs.

Every chapter is found to end with a selected bibliography, embellished by useful notes in the advantages and disadvantages of any particular book or article.

RHODES W. FAIRBRIDGE

Marine Ecology; by HILANY B. MOORE. P. 493. New York, 1958 (John Wiley and Sons, Inc., $9.50).—Since the monumental, two thousand page, *Treatise on Marine Ecology and Palaeoecology* appeared but one year before Dr. Moore's *Marine Ecology* it is interesting to compare their respective roles. Under the scholarly editorship of Hedgpath, the *Treatise* is a book of reference—a sort of tenth edition of Linnaeus; but it is not the book to hand a beginner or even an expert in another field wishing a quick grasp of what is happening in marine ecology.

Moore's book is about one sixth of the bulk of the *Treatise* and a determined student could read it in a few days; yet some consideration is given to almost every aspect of the field—physical and chemical factors, biological environmental factors, ecology of species and communities and distribution both regional and with depth. In attempting so much many topics have received rather short shrift. A couple of examples will illustrate the point.

At the present day probably no phase of marine biological work has more active investigators or is experiencing such rapid change than the study of "basic productivity" and the population dynamics of phytoplankton. In *Marine Ecology*, these topics receive two or three pages. The terse reference to Riley's work could be of little help to the beginner and exasperating to the initiated, a situation which is not improved by a couple of typographical errors.

Considerably more space is given to fish populations and their exploitation but the treatment is misleadingly over simplified. Here particularly, much could have been gained by a better choice of references. It is true that the definitive work in this field, Beverton and Holt's *On the Dynamics of Exploited Fish Populations* did not appear until 1957, but other earlier works should have been mentioned to give the thoughtful student some idea of the complexity of the problems.

Of course the truth is that all that is happening in marine ecology cannot be condensed into a book of this size. Both the strength and the weakness of Dr. Moore's study is that he has not really tried to do so.

Dr. Moore's earliest investigations concerned single species in the intertidal zone. Throughout the thirties the results of this work appeared in a series of papers that have seldom been equalled for insight, ingenuity and brilliant simplicity. All through his varied subsequent experiences he has never really moved away from this first love. His book, *Marine Ecology* is not a satisfactory summary of all phases of this vast field. But it is the finest autecology of the intertidal zone ever written. Here Dr. Moore is an excited adventurer and no one but a pedant could fail to absorbe some of his excitement. Let us be thankful that the author has not produced a dry balanced treatment of all aspects of his subject; but under the pretense of producing such a book he has given us something which should excite students for a long time to come.

E. F. THOMPSON

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